Optimising economic, environmental and social objectives:

A goal programming approach in the food sector

David Oglethorpe

Newcastle Business School

Northumbria University, Newcastle Upon Tyne, NE1 8ST, UK

Email: David.Oglethorpe@unn.ac.uk

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Abstract

The business decision environment is increasingly complicated by the emergence of competing economic, environmental and social goals, a notion typified by the current pressures of global economic instability and climate change targets. Trade-offs are often unclear and contributions by different actors and stakeholders in the supply chain may be unequal, but due to the interdependencies between businesses and stakeholders in relation to total environmental or social impact, a whole chain, simultaneous and strategic approach is required. Following a review of relevant literature and the identification of knowledge gaps, this paper introduces and illustrates the use of goal programming as a technique that could facilitate this approach and using real case evidence for alternative food supply chain strategies, at local, regional and national levels. The paper shows how the method can simplify a complex simultaneous decision situation into a useful and constructive decision and planning framework. Results show how *a priori* beliefs may be challenged and how operational and resource efficiency could be improved through the use of such a model, which enables a broad stakeholder appreciation and the opportunity to explore and test new environmental or social challenges.

Introduction

Although its definition varies and seems ever-evolving, sustainability remains a key term used to describe the desired outcome of systems that increasingly need to achieve a plethora of economic, environmental and social targets (Brundtland, 1987, through OECD, 1997, to Stern, 2006). This is no more apparent than at the current time where socio-economic instability is combined with an intensifying debate on climate change and the subsequent desire for global agreement on greenhouse gas emissions targets. However, although it is dominant and very much focused on the long term, the climate change agenda is not the only environmental concern facing business - water use and associated quality or air pollution are of major concerns to governments and will reflect regulation affecting business. So too, are the social dimensions of health, employment, welfare and so forth, issues that form the corporate social responsibility task confronting business.

As a result, the current decision environment facing business operations is multi dimensional and the achievement of multidimensional improvement relies not only on solutions to be sought within single operations, but relies on the interdependence of operations throughout entire supply chains (Figueira *et al*, 2005). This is primarily because the notion of environmental responsibility is entangled with the notion of supply interdependency not least because of the way in which the environmental burden of a product or service is calculated increasingly requires the use of life-cycle analysis techniques (Williams et al., 2006). Thus, any account of the environmental impact of any product or service, clarity of the entire supply chain and involvement of all supply chain participants is necessary, which extends upstream to an account of impact of contributions in design phases through to downstream use by the consumer and final disposal.

With this melee of objectives, it is often easy to ignore the complexity of the problems confronting business and focus on the simplest or most directly relevant issues – those associated with the economics of the business - cost and profit. This enables the business to focus on what it can control and reduces the focus both in terms of environmental externalities and the business to business relationships up and down the supply chain. As such, at times of economic instability we see a retreat to insular and protectionist behaviour, which is not beneficial in the long term (Busch, 2009). In addition, rarely do entire operators and stakeholders across supply chains come together to formulate strategy. However, this may simply be because formal systems are not routinely used to simplify the complexity of the situation into a single decision making framework that can both include an appraisal of the entire supply chain of different operations and also include objective setting for a variety of multi dimensional variables with private and public good implications.

The aim of this paper is to explore knowledge gaps in multi-dimensional decision making within the sustainability agenda, particularly focusing on the potential development of whole supply chain methods to aid private and public environmental planning. It looks at some of the origins of incorporating sustainability objectives into decision making, focusing in on the growing calls for the examination of multiple and competing objectives, introducing background literature on multi-criteria analysis (MCA). The paper then offers a possible solution through the application of a MCA mathematical programming technique, goal programming, which can enable such a framework to be available.

Literature foundations

Following Brundtland (1987), sustainability grew as a policy issue and inevitably led to the need to evaluate environmental damage or improvement and a body of literature emerged with environmental valuation at its heart. The purpose of environmental valuation was to attempt to internalise the environmental externalities of production into a formal cost-benefit analysis (CBA) as a framework by which economic and environmental objectives could be measured. Relevant as a genesis to multi-criteria decision making, key papers in the development of this literature include Barbier, Markandya and Pearce (1990), who introduced the concept of CBA as a means of measuring sustainability, followed by authors such as Turner et al. (1992), Hanley and Spash (1993), Willis et al. (1993) and Hanley (2001), who illustrated the use of environmental CBA to support policy decision-making. Much of the literature has, however, focused on methodological issues related to the accuracy and validity of environmental valuation and the transformation of environmental impacts into monetary values to enable multiple objectives to be considered in the same units, which in most cases used either hypothetical markets or proxy variables (Henderson and Bateman, 1996, Sterner, 1994 and Scheraga and Sussman, 1998, provide examples).

A key paper by Pires (1998), however, changed the focus of analysis somewhat by extending CBA to an operationalised project planning context for practical application, introducing sustainability constraints, rather than competing sustainability objectives. This paper was important because it provided a means by which transformation of variables into the same units was not necessary since physical environmental impacts could be represented directly. It is this aspect of practical application and comparison of variables measured on different scales and measured in different units that is valuable to a multi-dimensional sustainability debate, since it avoids issues of subjectivity in environmental valuation.

However, a common theme to such valuation studies in environmental economics is that application is usually to a single operation and deals with single end-point environmental outcomes rather than cumulative outcomes. A significant gap in this literature was the application to a set of combined supply chain activities and the resultant combined and cumulative economic, environmental and social impact that may vary according to different power structures between collaborating and competing business units. Since businesses now very much compete on a supply chain versus supply chain basis as opposed to business versus business (Zhang, 2006), this is an important gap in our understanding.

As a result, literature has grown on the environmental impact of entire supply chains, both from an internal (private business) perspective and from an external (public stakeholder) perspective. An important starting point for this research is provided by Carter et al. (1998), who called for more research that would enable managers to be able to weigh up qualitative environmental benefits against quantified economic costs. Carter's work has been invaluable in transforming this literature and further research by Carter et al. (2000), Carter & Jennings (2002) and Carter (2004 and 2005) explores the relationship between supply chain interactions and sustainable purchasing practices with respect to costs. A key outcome of this contribution has been to highlight the business value in increasing supply chain visibility and understanding of economic-environment interactions from a holistic point of view. Similarly, Doel (1999) suggested that although one-upstream and one-downstream relationships were becoming well understood, this remained focused on economic competitive advantage and led to modular rather than whole-chain decision making and suggested the establishment of decision frameworks that can look at the whole picture to explore governance decisions.

To a certain extent, this has been achieved in the logistics and distribution literature, where, due to the implications of fuel resource use, there are clear economic and environmental tensions. By enlarge, however, much of this literature continues to focus just on the logistics operations between producing operations, but has introduced some interesting methods involving multi-criteria analysis (MCA). Importantly, however, the literature also begins to make the connection between scale efficiencies from both an economic and environmental point of view (McKinnon, 2005, Aronsson and Huge-Brodin, 2006, and Kohn and Huge-Brodin, 2007, provide examples), but again much of the research transforms environmental damage into cost estimates based on environmental valuations, harking back to the weaknesses identified by Henderson and Bateman (1996), Sterner (1994) and Scheraga and Sussman (1998). Nevertheless, these weaknesses invoked greater exploration into the use of MCA in whole supply chain analysis.

Multi-criteria Analysis

In neo-classical economics, solutions for achieving socially optimal outcomes are drawn from the ethical premises of utilitarianism, credited to Pareto, who argued that any action that makes one person better off without making someone else worse off should be the underpinning rule of any socio-economic policy. Such a policy could be that of government or of business, but in essence, what Pareto was saying was that trade-offs always occur, but the trade-offs that should be selected should be those that increasingly improve the overall situation. A more realistic interpretation of this that is taken by analysts who deal with combined economic, social and environmental issues is to subscribe to Pareto’s rule as a moral tenet but which should guide decisions towards actions that generate ‘the greatest good for the greatest number’ (Daly and Cobb, 1989).

Multi-Criteria Analysis (MCA) follows from this theoretical underpinning by accepting that both business and policy decision-making are multi-dimensional and that there exists a multiplicity of economic, environmental and social values that form business decisions, all of which may be measured in different units and on different scales. In essence, MCA is formed upon the premise that there are many and, at times conflicting, economic, environmental and social preferences but that a consensus should be sought instead of a ‘satisfaction-for-some and compensation-for-rest’ approach, which might arise as a result of a simple cost-benefit analysis of a two dimensional problem. This also underpins some of the arguments recently proffered by Carter and Rogers (2008) who look, *inter alia,* at the development of a ‘triple bottom line’ conceptual model and the introduction of scales to measure it. Their paper supports the use of MCA but highlights an important and currently missing contribution – the ability to simultaneously consider variables across different scales and across different decision dimensions of economy, environment and society. Carter and Rogers allude to this (and in doing so echoing earlier research by Joubert *et al*., 1997) by describing different sets of weighting conditions involving different overlays of economic, environmental and social outcomes from different stakeholder viewpoints.

Insights into the use of MCA within sustainable supply chain analysis are provided by Minner (2003) through the examination of multi-inventory constraints and activities but uses only single objective criteria, whereas Agarwal et al. (2006) and Ng (2008) use multi-objective scenarios represented by incorporating variables measured on different scales and in different units. However, these studies still remain focused on multiple objectives within the single dimension of operational efficiency, rather than wider environmental or social goals.

Amid *et al.* (2006) explore the incorporation of vague information and data paucity within an MCA framework using max-min criterion to capture variation and missing information, and Ilbery and Maye (2005) identify the complexities and operational sharing within supply chains that culminate in similar products but with different environmental characteristics. This latter point is important since it points to the opportunity to capture these complexities as constraints and activities within a planning model. Wiskerke (2003) discusses technical and institutional constraints in supply chains, showing the relevance to external stakeholders within planning decision making and supports the notion that in the absence of significant power, single actors cannot take social responsibility for total supply chain impact, in line with the public good characteristics of wider environmental and social planning. Towards the development of a formal decision support tool, Maloni and Brown (2006) provide a series of factors that are important in making Corporate Social Responsibility decisions in the food sector and amongst their conclusions they suggest an extension would be to create a formal decision making platform, incorporating multiple goals, but there appear few attempts to do so.

In summary of this literature, there appears to be a gap in knowledge or application regarding a three-way issue: the ability to examine the trade-offs between the potentially competing economic, environmental and social objectives facing the entire supply chain of a product or service; the contribution to each of those objectives of each operation within the supply chain and the logistical connection between them; and, the requirement to be able to weight the importance of each of those objectives according to business or stakeholder view. This paper now attempts to provide such a framework through the development of a Goal Programme, an MCA approach that most suits the planning decision problem framed in this paper.

Goal programming

A conventional approach to optimising objectives relating to competing activities and subject to resource availability is to use mathematical programming. Where we have only a single objective, this can be achieved through the application of linear programming (LP), but the single objective limitation of LP models has been identified as a significant limitation on their use, synonymous with some of the limitations highlighted in relation to CBA. This shortcoming has been overcome, however, by the development of multiple objective functions integrated into LP, providing the ability to incorporate distinct and even conflicting objectives in the examination of resource allocation issues.

Multi-objective models include complex and diverse criteria while at the same time investigating alternatives in order to eliminate the less desired options (Werczberger, 1976; Cocklin *et al*., 1986; Romero & Rehman, 1987). In this context it is important to underline that solutions represent a satisfactory compromise between conflicting criteria and not necessarily the ‘optimal result’ for any one criteria. Rather, they can be used to assess the best use and configuration of resources, which supply chain strategies to adopt and how to vary operation activities in order to achieve a set of pre-defined goals, hence, Goal Programming (GP).

The essence of GP comprises an effort to minimise the deviations between the desired target levels of achievement for each goal and the levels possible to be achieved in practice, under the constraint of parallel satisfaction of other goals. The target to be achieved for each goal may simply be to reach a minimum or maximum or it may actually be some pre-defined level, such as that set by an external regulating body (emissions or pollutant targets, for example). However, where absolute targets are used, the extent to which a goal is not achieved represents the trade-off that has to be sacrificed for other goals to be met. What is therefore more useful is to model all goals as either achieving the lowest value possible (for negative attributes such as greenhouse gas emissions or other environmentally damaging outputs) or highest value possible (for positive attributes such as profit, jobs, health etc.) given the circumstances of the system under consideration. Each goal can be subjectively weighted to represent the views of different stakeholders who, for example, may want to explore how supply chain operations need to change in order to provide a solution more heavily weighted towards environmental, economic or social goals.

Goal Programming can thus, in theory, provide a solution for filling the three-dimensional knowledge gap identified above in that it can examine the trade-offs between objectives, incorporate physical supply chain operations as activities and constraints within the model and enable stakeholder weighting in use. This paper explores the practical application of that theoretical basis.

Mathematically, and following Hazell and Norton's (1986) original postulation, a GP is represented algebraically as:

$$Maximise \sum_{i=1}^{n} (w_i g_i)$$

$$subject\ to \quad f_i(x) + n_i - p_i = b_i$$

$$and \quad x \in F$$

with x, n and p all non-negative

Where g_i is the goal for the ith attribute, the target for which (b_i) will either be set to zero for a negative attribute (to be minimised) or infinity for a positive attribute (to be maximised), and w_i is the weight attached to the ith goal. In addition, n_i and p_i are the negative and positive deviational variables attached to the ith attribute, respectively, $f_i(x)$ is the function for the vector of activities (X) that defines the contribution of those activities to the goal for the ith attribute and F is the feasible constraint set.

This formulation assumes that we can directly trade attributes that are measured on different scales, which may seem unnerving, but means that the shadow prices produced by the model will reveal the trade-offs necessary to create gains in competing goals. Further, as long as at least one of the goals is a monetary term, each can be compared as to the real opportunity cost of changing priorities.

Application

Any GP model is defined by the resources, activities and objectives (goals) it recognises and uses from the system it examines, by the constraints limiting the activities and importantly, by the issue it is examining that is of policy or business interest. Any GP therefore needs to be constructed to tackle a specific issue and information and data to calibrate the model needs to be taken from a specific study problem to represent a typical set of competing activities. The GP that is set up and tested here, to demonstrate the application to current issues facing business and in particular to those facing a whole supply chain, represents an issue facing the food sector. The following sections describe how the GP model is defined by the issue it is designed to tackle, the goals it employs and by the alternative activities it will allow trade-offs to occur between.

The issue

The food sector is somewhat unfortunate in that it attracts much attention from environmental lobbyists due to its emblematic and highly visible nature wherein we are all consumers (Oglethorpe *et al*, 2008). Due to an increasingly environmentally-conscious consumer, the sector, and in particular its retailers and their buyers, has also been at the forefront of setting challenging greenhouse gas related objectives, notably through its visible distribution networks and supply chain partnerships.

Within the sector, a means of achieving environmental and social benefit has involved movement towards a ‘localisation’ of supply chains. This is grounded in the ‘food miles’ debate but is in fact more complex than its face value. There is substantial variation in the quality and medium of literature presented on the environmental impacts of food, from academic articles grappling with definitional and theoretical postulations, to radio and television programmes, hosted by celebrity chefs or environmental lobbyists. Much of the media led activity has involved a popular movement against large scale food suppliers, retailers and distributors and this is typified by the food miles lobby, initiated through a concept put forward by Pretty et al (2005). This concept has undoubtedly had an unintended effect and has been taken more literally than initially desired by its founding academics where the initial intention was more sociological in content, challenging the increasing globalized food market (Winter, 2005; Sage, 2003; Morris and Buller, 2003; Cowell and Parkinson, 2003). However, the popularity and inertia of the ‘food miles’ concept has led to an almost overt notion that the more ‘local’ produce is, the better it must be for the environment (e.g. FWI, 2006). This has spread further and we tend to think of local procurement as a good thing for the environment without really thinking through what the aggregate effects might be.

In economic terms, the notion of deliberately localising the supply of any product when economies of scale are available, defies basic theories of comparative advantage. As Ricardo pointed out as far back as 1817, economic development happens because it is beneficial for two or more economic agents to specialise in production and trade with each other, rather than try to produce everything themselves. *Ergo*, economic development is typified by a movement away from subsistence agriculture and local trade and this is why we now have a global marketplace, with huge improvement in choice and significant exploitation of economies of scale through sophisticated supply networks.

As a result, it is becoming increasingly accepted, at least in the academic literature and amongst industry practitioners, that more efficient use of resources *per unit of output* makes sense both in an economic and environmental context. This reflects the literature mentioned previously by authors such as McKinnon (2005), Aronsson and Huge-Brodin (2006) and Kohn and Huge-Brodin (2007) and it is this qualification that makes the argument more sensible. Total consumption is more or less stable in the short to medium term and as such we need to be concerned about the impact that production has on any environmental or social attribute per *unit of output*, not simply in total. Given these possible conflicts, the option to 'localise' is potentially a worthwhile topic to use to examine different supply chain planning responses to a variety of goals, since it remains controversial and a potential point of product differentiation.

Goal selection

Clearly, a vital consideration within the construction of the GP is the choice of which goals to use to represent the multi-criteria economic, environmental and social (EES) decision environment. This selection also needs to be based on evidence of importance from both the literature and in terms of industry priority. Globally, the food supply chain, including agriculture, contributes to around 13.5% of total greenhouse gas (GHG) emissions (UNEP/GRID, 2005). This pressure has meant the food sector, and in particular the large multiple retailers, have often had to set the pace for the response to the climate change agenda and both firm level and country level goals relating to Carbon Dioxide-equivalent emissions are being set. In a similar regard, the food sector comes under pressure to provide healthy lifestyles through the provision of nutritious and healthy products, with fat content being an obvious target in light of western obesity problems. However, the sector remains fast moving and highly competitive and the cost-efficiency of operations and associated logistics services remains a central concern to producers in order to make a good return on sales.

In a survey of local food literature, Tregear *et al*. (2007) provides a summary of the EES impact categories that occur most frequently in studies attempting to measure the impact of food chain localisation, where the headline economic categories are: returns to producers; value retained in local community; product quality and consumer price, the key environmental categories relate to energy use, CO_2 emissions and agricultural practice, and the social variable of most interest is rural community vibrancy. Alternatively, Oglethorpe and Heron (2009) followed Agarwal *et al.* (2006) to produce a template analysis of narratives held with supply chain operators and other industry stakeholders to reveal EES impact categories deemed important within the food localisation debate. This analysis produced similar categories as provided by Tregear *et al*. (2007) but added water use as an important environmental issue and both the number of jobs and health as important social dimensions.

Of particular importance from an economic point of view, given the characteristic of late product differentiation, is the difference in value added at retail stage (supported by Defra, 2003, Renting et al, 2003, Morris and Buller, 2003, and De Roest and

Menghi, 2000). Within environmental objectives, greenhouse gas emissions, proxied by carbon dioxide equivalents, attracts most attention (e.g. Saunders, 2006; Darnall et al., 2008) but water use is also increasingly seen as a sensitive variable (Reich-Weiser et al., 2008). From a social perspective, whilst re-connection and community vibrancy are important, these are notoriously inter-twined with non-sector specific and pre-existing social cohesion factors (Brunori and Rossi, 2000) but two key attributes that are more tangible and measurable are employment in terms of numbers of jobs in relation to sales volumes and health impacts, particularly related to sugar and fat content of products which are often higher in local food products that tend to satisfy a more indulgent and luxurious food tastes (Oglethorpe & Heron, 2009). Fat content in particular could be viewed as a potentially more serious problem than sugar content due to the association with hardening of blood vessels and heart disease and has also been found to have a closer direct relationship to weight-gain than sugar content (Gibson and Neate, 2007).

As such, it may be plausible to suggest that there are five key goals associated with modern food production that reflect both private and public decision making priorities: Return on sales; greenhouse gas emissions; water use; fat content of products; and, number of Jobs. It is clear that the first and last of these would be seen as positive attributes, whilst the remaining three are negative (in the sense that more of them is a bad thing).

So, we have five central goals that the food supply chain must contribute to or reduce the impact of within the context of the 'localisation' issue. The next stage within model specification is to define the activity and constraint set that form the basis of alternative supply chain strategies that reflect different options within the 'localisation' debate.

Activity definition

Three alternative activities are defined that differ by the geographic spread and scale of their production, processing, manufacturing and retail operations and associated distribution networks, named here simply as 'local', 'regional' and 'national'. Data for each of these alternatives is taken from a survey conducted by the author of three representative supply chains, each of which culminate in the retailing of pork products and we have chosen to simplify this by focusing on the main selling product at each retail outlet – pork sausages. This survey involved a physical supply chain mapping exercise where the scale and geographical reach of each supply chain was identified and the physical resource input and intermediate output at each supply chain stage was recorded. All survey participants from each supply chain stage verified the data as correct for their operations. As such, the options appraised by the model represent a real-world planning problem faced by a real set of businesses.

For each of the three potential supply responses, we need to construct the activities involved, identify the resource needs of each and in particular, calculate the contribution that the use of those resources and the undertaking of the activity make to each of our five goals. The construction of the three alternatives is discussed below in relation to the different operations involved throughout the supply chains. However, an important feature to note of the supply chains examined is that they share many of the same operations and the differentiation achieved through a 'localisation' strategy occurs at quite a late stage of the supply chain (as noted also by Ilbery and Maye, 2005). The pigmeat for all three supply alternatives are supplied through a regional abattoir which in turn is supplied with pigs from same the farm. The local outlet takes approximately 2% of the total number of pig carcasses, the regional outlet takes a further 10% and the remainder enter the national chain. As such, only the final processing/retailing environments differ within the three supply chain alternatives. The pigs reared for all supply chains are effectively identical - they are fed on the same diets and rations, using the same feed inputs, primary crops and crop inputs. As a result, the alternative strategies to be compared within the goal programme only need to include those activities and constraints which differentiate the three alternatives. The following sections describe those activities and constraints and Table 1 at the end of the section, summarises total contribution to each goal area from each supply route.

The Local supply chain

For the local option, the pig carcases are transported from the abattoir to a farm shop, which incorporates a butchery to undertake final processing into sausages (refrigerated at all times). The consumer then drives to the farm shop to purchase the sausages, which are simply wrapped, thus excluding the need for national or regional distribution centres. Sausages retail for £5 per kilo, have a fat content of 10% and the store hires a labour force equivalent to 0.08 hours per kg of output. In addition, the operations use water in both processing and cleaning, in total using 10 litres of water per kg of output. The contribution to the goals of return on sales, fat content, water use and number of jobs are thus easily defined. The contribution to the goal for CO_2 emissions is slightly more complicated since CO_2 emissions are association with overhead operational energy consumption, distribution operations and packaging.

Operational energy consumption is generated from refrigeration of meat during processing and storage before purchase, basic mixing and blending machine use and the heating and lighting of the retail operation itself. Total energy use for these overhead operations is recorded as having an equivalent greenhouse gas emission of 2.1 kg CO_2 per kilo of output. Distribution costs include the movement of the carcases from the abattoir to the shop butchery and the trip made by the customer to buy the sausages at the shop. The former involves a return journey of 54.7 miles and is made by a 7.5 tonne capacity rigid vehicle at a 39% average load (2.925 tonnes). Defra (2008) provide an estimate of CO_2 emissions from such a vehicle as being 0.901 kg CO_2 per mile travelled. Per kilo of produce transported this equates to 0.0003 kg CO_2 per mile, giving a total emission of 0.01641 kg CO_2 per kg of produce.

In terms of the customer journey, the nearest major town is 11 miles away, but our survey evidence suggests that the actual customer base is wider, however in the absence of specific consumer demographic evidence, we will assume that the 'average' customer comes from this town and so the average total customer journey is 22 miles. The corresponding estimate of CO_2 emissions from an average petrol car as being 0.3372 kg CO2 per mile travelled (Defra, 2008). The average consumer purchase was recorded as 2 kg of produce and so per kilo of produce transported this equates to 0.1686 kg CO_2 per mile and for the total return average customer journey this equates to a total emission of 3.7092 kg CO_2 per kg of produce. From comparison of these two figures, one can immediately see the economic-environment synergy within the greenhouse gas/climate change debate – the use of larger scale vehicles vastly reduces the emissions per kilo of product.

Packaging of the produce simply involves the use of an unlabelled unmarked plastic slip bag, which can contain 1 kg of produce, weighing approximately 5g. The greenhouse gas emissions associated with plastic packaging is recorded as 4.95 kg CO_2 per kg (Time for Change, 2009) and so the associated greenhouse gas emissions for packaging within this chain is 0.0245 kg CO_2. The total CO_2 emissions from operations, distribution and packaging are thus 2.1 + 0.01641 + 3.7092 + 0.0245, which equals 5.85011 kg CO_2 per kg of produce.

The Regional supply alternative

The definition of this alternative lies in the focus of the retail operations involved, which comprise a series of small to medium sized mixed good outlets throughout the region, which are all within an 80 mile radius. The average retail price for the sausages at these outlets is £4 per kilo but the sausages have a higher fat content of 15%. This higher fat content is reflective of the different processing operations involved compared to the local chain. In this case, the pig carcases are processed on site at the abattoir in a large scale operation that then sells processed products on to both this regional and the national chain. The energy use of the processing operations at this site equates to an emission of 0.9 kg CO_2 per kg of output and in total 8 litres of water are used per kg of output. The average regional retail outlet has energy costs associated with refrigeration plus basic heating and lighting, the total of which equates to an emission of 0.6 kg CO_2 per kg of total sales. Total energy emissions in all operations throughout this ‘regional’ chain are therefore 1.5 kg CO_2 per kg output.

A greater weight of primary and secondary packaging is associated with this network, however, and in addition to the direct product packaging and labelling, there is additional wrap packaging in transportation. The total amount of plastic used in all these packaging operations is estimated at 0.03 kg per kg of output and again, the greenhouse gas emissions associated with plastic packaging of 4.95 kg CO_2 per kg (Time for Change, 2009) is used and so the associated greenhouse gas emissions for packaging within this chain is 0.1485 kg CO_2.

Following processing, the sausages are packaged and labelled with the meat processing company logo and label and distributed to the retail outlets. The average return journey of this distribution stage is 120 miles and again is made by a 7.5 tonne capacity rigid vehicle at a 50% average load (3.725 tonnes). Using the Defra (2008) source as above, CO_2 emissions from such a vehicle are 0.914 kg CO_2 per mile travelled. Per kilo of produce transported this equates to 0.0002 kg CO_2 per mile and so, the total emissions from this distribution stage are 0.024 kg CO_2 per kg of output. Given the geographical spread of retail outlets within the region, the average car journey made by customers is assumed to be five miles, which again, using the same data sources and assuming the same purchased quantities as with the local chain, equates to a total emission from this distribution stage of 0.843 kg CO_2 per kg of output.

The total CO_2 emissions from operations, distribution and packaging are thus 1.5 + 0.024 + 0.843 + 0.1485, which equals 2.5155 kg CO_2 per kg of produce.

Due to the expanded operations, the wider variety of foods sold and the larger processing facility in this chain, the combined labour use of the retail store and the processing operation is equivalent to 0.005 hours per kg of sausage sales.

The National supply alternative

This chain involves movement of the product from the same processing facility as in the Regional alternative through to a national distribution centre with onward movement to a multiple retail environment (supermarket). In this case, due to the separation of logistics operations, the average distances involved include a 36 mile journey from processor to distribution centre by 7.5 tonne capacity rigid vehicle at a 50% average load (0.0002 kg CO_2 per kg product mile travelled as above, or a total of 0.0072 kg CO_2 per kg of product) and then an average journey by articulated 33 tonne capacity HGV of 110 miles from distribution centre to store. Defra (2008) provide an estimate of CO_2 emissions from such a vehicle as being 1.4864 kg CO_2 per mile travelled at an average full-running rate of 59% (19,470kg). Per kilo of produce transported this equates to 0.00008 kg CO_2 per mile and a total of 0.0088 kg CO_2 per kg of product.

Although exact data were not available, we assume here that the average consumer journey to a supermarket is 1 mile (i.e. 2 miles round trip) and is travelled by car. Clearly some journeys are longer, but some are also on foot or by public transport. We also assume that the average total shopping purchase per trip is 10 kg and this reflects the cars payload. That component of the transport greenhouse gas burden in the national supply chain is therefore 0.3372 kg CO2 per mile carrying 10 kg of produce, which equates to 0.0674 kg CO_2 per kg of produce for the two mile trip.

The supermarket retails the sausages at £3 per kilo but the sausages have the same fat content as in the Regional network (due to shared processing) of 15%. The retail operation is very large and as such can spread its energy cost across a large amount of product throughput and the total emission-equivalent of energy use for refrigeration, heating and lighting is 0.1 kg CO_2 per kg of produce sold. Added to the processing operations emissions of 0.9 kg CO_2 per kg of output (see the Regional chain data), total operations emissions are equivalent to 1.0 kg CO_2 per kg of output. Water use is also the same as for the Regional operation.

An even greater weight of primary and secondary packaging is associated with this network, however, and on top of the packaging present in the Regional network, there is additional order-separation wrap packaging, boxing and palletisation in transportation. Although there is some re-use of boxes, plastics and pallets, the total amount of plastic used in all these packaging operations, which is not re-used, is estimated at 0.05 kg per kg of output and again, the greenhouse gas emissions associated with plastic packaging of 4.95 kg CO_2 per kg (Time for Change, 2009) is used and so the associated greenhouse gas emissions for packaging within this chain is 0.2475 kg CO_2.

Again, due to the economies of scale and the wide variety of food and other products sold in the retail environment of this chain, the combined labour use of the retail store and the processing operation is equivalent to 0.0002 hours per kg of output.

The three supply alternatives therefore have a set of goal contributions associated with their activity as summarised in Table 1, which are used directly within the GP model to represent the function as defined by f_i (x) above, where *i* in each case is the local, regional or national supply alternative, respectively.

Table 1 Summary of supply chain goal contributions per Kg of Output

	Local	Regional	National
Kg CO_2	5.85011	2.5155	1.3309
Litres of water use	10	8	8
Kg of Fat	0.1	0.15	0.15
Retail price (£)	5	4	3
Hours of employment	0.08	0.005	0.0002

These data were used to construct and calibrate the GP model, which also included activities for the attainment for the five goals - sales, greenhouse gas emissions; water use; fat content and jobs. The final constraint that was entered into the model was that of total consumption. For this, we identified an upper limit of 35,000 tonnes of sausages, equivalent to the average national annual consumption for the UK (Defra, 2009). The GP can thus be used to help decide by which supply strategy this demand could be met according to the desirability of different goal achievement, which can be represented by allocation of different weights to the goals.

Results for alternative goal weighting allocations

The model was initially run (using MS Excel Solver) identifying equal weights to each of the five goals. For the purposes of this illustration, the model is constrained to recognise the three competing activities as being mutually exclusive and the model simply identifies which one of the three activities maximises the outcomes against the goals, given the relative weights imposed on each. For a more sophisticated analysis, we could expand the model to incorporate options to enable multiple and mixed supply strategies to be invoked. The key activity and sensitivity results of this first non-weighted scenario are reported in Table 2.

Table 2 Summary GP Model output – equal goal weights

	Solution Value	**Allowable Increase**	**Allowable Decrease**
Supply Chain Strategy			
LOCAL	0		
REGIONAL	35,000,000		
NATIONAL	0		
Goal attainment			
WATER USE (litres)	280,000,000	3	∞
FAT CONTENT (kg)	5,250,000	∞	129
CO2 (kg)	111,490,956	1	0
SALES (£)	140,000,000	6	0
JOBS (hours)	175,000	86	40

As Table 2 shows, the basic solution of the model suggests that given an equal weighting of the goals, the rational choice is to select the Regional supply strategy and to maximise the benefits to the five mixed environmental, economic and social goals. In essence, what the model output tells us is that this is the optimal solution but only for these weightings and suggests, for example, that to create sales of £140m, we will incur a carbon footprint of approximately 111m kg CO_2 through this supply strategy. This does not really mean anything to us, except to say that each unit of value is roughly equivalent to a unit of global warming potential, but it does immediately identify which supply strategy is ‘best’ from an equal stakeholder weighting of the five goals.

However, the allowable increases and decreases in the sensitivity analysis go some way to explaining how the situation could change if the goal weightings changed and thus how the relative trade-off between goals and the importance attached to each might change things. What it suggests, for example, is that if we weight the goal on sales by six times as much as other goals, and hold the other goals constant, the basic solution will change. Doing this provides the results presented in Table 3.

Table 3 Summary GP Model output – Sales goal weight = 6, others 1

	Solution Value	Allowable Increase	Allowable Decrease
Supply Chain Strategy			
LOCAL	35,000,000		
REGIONAL	0		
NATIONAL	0		
Goal attainment			
WATER USE (litres)	350,000,000	∞	1
FAT CONTENT (kg)	3,500,000	31	∞
CO2 (kg)	305,834,226	∞	0
SALES (£)	175,000,000	∞	2
JOBS (hours)	2,800,000	∞	21

In this scenario, sales now increase due the increased emphasis and the highest yielding activity, Local, is selected. However, this 25% increase in sales also enables a significant improvement in jobs and a 33% reduction in fat content but is at the cost of a 174% increase in greenhouse gas emissions and a 25% increase in water use. Importantly then, the result starts to inform us about how the selection of different supply chain strategies will lead to different multi-dimensional outcomes.

Given the complexity of the decision environment and the number of variables included even in this simple problem, it would have been difficult to foresee how each economic, environmental or social variable was inter-related and how each might move in harmony or in opposition with each other. Using the goal programme and its associated output, the picture starts to become clearer.

The results also provide insight into some interesting concepts that may contradict *a priori* expectations. As mentioned in the introduction to the problem, the concept of 'local' in the food sector has become synonymous with environmental improvement as a pre-conceived notion. However, as was also noted, this would appear to contradict basic theories of comparative advantage and economies of scale in that specialisation, trade and falling marginal costs with scale suggest that as operations become larger, they become more resource efficient. Taken literally in terms of energy use (as a natural resource) one would therefore expect the larger scale operations to have more efficient resource use per unit of output and therefore a lower overall emission of greenhouse gas for the aggregate supply of 35,000 tonnes in this example.

As Table 3 shows, movement away from the medium scale option of a Regionally-based supply network to a local network incurs an increase in greenhouse gas emissions. This fits with the theoretical reasoning. In addition, if we look back at Table 2, the allowable increase on the weight of the greenhouse gas goal is just a factor of 1, which suggests that if we vary the weight of this goal to two, keeping all other goals at a weight of one, we should get another (and presumably different) result than that presented in Table 3. Table 4 presents the model output from a re-run of the model with this weighting change.

Table 4 Summary GP Model output – Greenhouse Gas goal weight = 2, others 1

	Solution Value	Allowable Increase	Allowable Decrease
Supply Chain Strategy			
LOCAL	0		
REGIONAL	0		
NATIONAL	35,000,000		
Goal attainment			
WATER USE (litres)	280,000,000	6	∞
FAT CONTENT (kg)	5,250,000	∞	252
CO2 (kg)	83,015,958	1	∞
SALES (£)	105,000,000	1	∞
JOBS (hours)	7,000	130	∞

As Table 4 shows, and as economic theory would confirm, the more resource efficient supply chain option is now selected. If we look back and compare the data that is summarised in Table 1, the National supply chain had the greatest use of the most efficient transport per kg of product (the HGV) and also had the lowest energy related emissions from operations, due to its scale. Table 4 now suggests that although this is now the most efficient option for climate change, the 26% reduction in CO_2 emissions is achieved at the cost of a 25% reduction in sales and a 96% fall in jobs.

Conclusions

Although this example represents a relatively simple decision situation and the different planning choices are limited to three distinct options, the approach enables a situation that is complex both in terms of the requirement to simultaneously judge the importance of competing pressures on the business and in terms of the number of decision variables involved, to be made simpler. Once constructed, the model enables substantial interrogation and use of its output to investigate how changes in the weighting of goals might lead to a different strategy to be selected. It also provides a platform for understanding how change in any of its technical variables could change the overall situation. For example, after examining the output presented in Table 4 and appreciating that there was a better solution for greenhouse gas emissions available, the model could be used to test the extent by which the resource efficiency of the 'Regional' solution needed to change to make it a better option for greenhouse gas emissions. This could be achieved by improving the efficiency of operations or logistics activities, but the key point is that the model would enable an assessment of by *how much* the efficiency would have to change, which could help inform environmental business decisions or policy making for public good attributes.

A further application of the model could be to provide the opportunity to test new or hypothetical strategies with regard to their impact on the different goals or to explore the impact of existing strategies on new goals. As a mathematical programming technique, the model is not dependant on historical data for its use (unlike comparative econometric forecasting models) and as such can test hypothetical scenarios. Even in the absence of technical data for such new or hypothetical activities, sensitivity analysis allows different technological coefficients to be tested and so the model can still be used successfully. Such an extension might be to explore the impact on a new economic, environmental or social goal such as market share, air pollution or food safety.

What is most useful about using such an approach however, is the simplification it can make to a whole chain decision environment which is both useful to the private operators across the chain in a strategic context but is also useful in a policy context to test public good impacts. Through a formal representation of supply chain activities and the contribution by those activities to competing economic, environmental and social objectives, it enables us to examine weighted trade-offs between those objectives according to different business or stakeholder positions, thus making the contribution to the literature outlined earlier.

With an increasing focus on a wider variety of production goals across the economic, environmental and social spectrum, decisions increasingly need to involve a wider network of supply chain partners and stakeholders because their individual actions have repercussions for one another. It is unlikely that this network will be involved in detailed operational decisions, but will need to look strategically at how it configures the whole chain and what supply strategies to pursue. This will in turn then affect decisions over individual operations. The model presented here provides a platform on which to base and facilitate those strategic decisions so that all those involved in the planning or decision process can contribute to the same set of environmentally, socially and economically optimal goals.

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