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Providing Efficient Decision Support for Green Operations Management: An Integrated Perspective

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1. Introduction

Green operations management (GOM) has emerged to address the environmental and social issues in operations management, so that the Triple Bottom Line (3BL) sustainability can be achieved simultaneously (Rao & Holt, 2005; Zhu, Sarkis & Geng, 2005). The concept of GOM was originally formed in the 1990s. Early research on GOM mainly directed towards segmented areas of operations management, such as quality management. Over the past decades, GOM has attracted significant research interests from academia, many issues remain under-addressed which have hindered the effectiveness of GOM practice (Zhao & Gu, 2009; Yang et al, 2010), although the needs for and benefits of GOM cannot be overemphasised for sustainable development (Svensson, 2007). One of the main reasons for GOM lagging behind quality management advances has been identified as lack of true integration of environmental and social objectives into business operations, i.e. environmental management and social values were viewed as narrow corporate legal functions, primarily concerned with reacting to environmental legislation and social codes of practice. Subsequently research and managerial actions focused on buffering the operations function from external forces in order to improve efficiency, reduce cost, and increase quality (Carter & Rogers, 2008; White & Lee, 2009). Research further reveals that the root cause behind the company's isolated approach to the 3BL sustainability is not because the managers do not appreciate the importance and urgency of addressing them, but lack of efficient support for the management of the complexity of sustainable decisions, especially the provision of powerful analysis approach to support effective decision evaluation (Hill, 2001; Taylor & Taylor, 2009; Zhao & Gu, 2009).

This paper proposes an integrated sustainability analysis approach to provide holistic decision evaluation and support for GOM decision making. There are two key objectives to explore the integrated approach: (a) to understand the GOM decision support requirements from a whole life cycle perspective; (b) to address the GOM decision support issue using multiple decision criteria. Based on a case study in production operations area, the paper concludes that the integrated sustainability analysis can provide more efficient and effective support to decision making in GOM.

This chapter is organised as follows. Next section reviews related work on methods and tools that have been developed to address GOM decision issues, and identifies the gap in literature. Section 3 proposes an integrated approach for systematic analysis of sustainability in GOM. Application of the integrated approach to real operations situation is discussed in Section 4. Then Section 5 reflects on the strengths and limitations of the proposed approach, and draws conclusions.

2. Related work

Sustainability or sustainable development was first defined by the World Commission on Environment and Development as the "development that meets the needs of present generations while not compromising the ability of future generations to meet their needs" (WCED, 1987). It has then been recognised as one of the greatest challenges facing the world (Ulhoi, 1995; Wilkinson et al, 2001; Bateman, 2005; Espinosa et al, 2008). For development to be sustainable, it is essential to integrate environmental, social and economic considerations into the action of greening operations (i.e. the transformation processes which produce usable goods and services) (Kelly, 1998; Gauthier, 2005; Lee & Klassen, 2008), as operations have the greatest environmental and social impacts among all business functions of a manufacturer (Rao, 2004; Nunes & Bennett, 2010). In the context of sustainable development, operations have to be understood from a network's perspective, that is, operations include not only manufacturing, but also design and supply chain management activities across products, processes and systems (Liu and Young, 2004; Geldermann et al, 2007). Without proper consideration of inter-relationships and coherent integration between different operations activities, sustainability objectives cannot be achieved (Sarkis, 2003; Zhu et al, 2005; Matthews et al, 2006). There has been a series of overlapping endeavours and research efforts in literature aiming to address the environmental and social issues in operations management, but earlier efforts have been mostly segmented and uncoordinated. More recently, GOM has been investigated from a more integrative perspective instead of a constraint perspective, where environmental management and corporate social responsibility are viewed as integral components of an enterprise's operations system (Yang et al, 2010). It means that the research foci have shifted to the exploration of the coherent integration of environmental and corporate social responsibility with operations management through business managers' proactive decision making (Ding et al, 2009; Liu et al, 2010). Figure 1 illustrates the key ideas of achieving sustainability objectives through holistic decision making in a sustainable operations system. Compared with traditional open operations model, i.e. the input-transformation-output model (Slack et al, 2010), there are four key features in the sustainable operations system:

1. A sustainable operations system is a closed rather than an open system, i.e. the material (including waste and used products), energy and information produced by the operations system should be treated and fed back as inputs to keep the system self-sustainable;
2. The transformation process not only includes the functions and activities that produce products and service, but also includes that of environmental and social improvements;
3. Wider stakeholders' requirements need to be addressed. Apart from customers, other important stakeholders include environment, community, employee, public etc. Therefore, the requirements such as discharge from operations process, information and social benefits have to be properly addressed;

4. The role of suppliers is changing. Apart from the provision of materials, energy, information and human resources, suppliers are also responsible for recovering used products and materials.
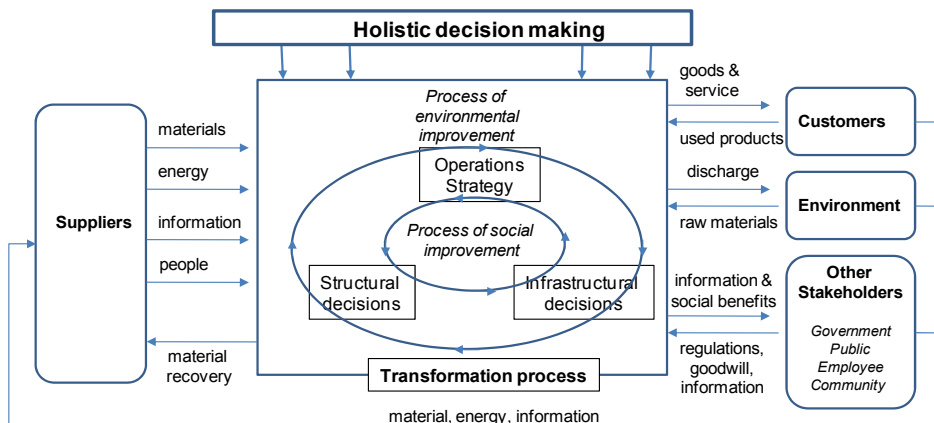

Fig. 1. Holistic decision-making in a sustainable operations system

Many decisions have to be made for green production operations in relation to design, manufacture and supply chain management (Sakis, 2003; Galasso et al, 2009). Slack et al (2010) classified operations strategic decisions into two main categories: structural and infrastructural. Structural decisions are those which primarily influence design activities, such as those relating to new product design and supply network design, while infrastructural decisions are those which influence manufacturing planning and control, and management improvements, such as inventory management and supplier development. Miltenburg (2005) defined six production decision areas: production planning and control, organisation structure and control, human resource, facilities, sourcing, and process technology. This classification scheme was also adopted by Choudhari et al (2010), and 54 decision types were further identified under the six decision areas with 113 decision alternative suggested for the decision types. However, the papers did not provide discussion on how the optimal decision choice could be reached for each decision type. There has been a broad consensus that decision evaluation holds the key to reaching optional decision choice especially under complex decision situations (Mehrabad & Anvari, 2010). Decision evaluation enables decision makers to perform scientific analysis, to weigh, score and rank the alternatives against decision criteria, and to assess the consequences of each decision alternative, so that optimal decision choices become more transparent to decision makers (Karsak & Ahiska, 2008; Chituc et al, 2009). In recent years, sustainability analysis has emerged as an important decision aid to provide efficient and effective decision evaluation in all aspects of business (Hodgman, 2006). Sustainability analysis is important to operations research because decision making in GOM often has high complexity, cost and risk. Getting the decisions right will generate not only considerable economic value, but also great environmental and social impacts which can sharpen a company's competitive edge (Noran, 2010).

Sustainability analysis would be theoretically straightforward if key interacting variables and boundaries of responsibilities were well understood by decision makers (Mihelcic et al,

2003). Unfortunately, such situations are rare, while benefits from sustainability efforts have been elusive. Practitioners continue to grapple with how sustainability analysis should be undertaken, due to the complexities and uncertainties of environmental systems involved and imperfections of human reasoning (Hertwich et al, 2000; Allenby, 2000). According to Hall & Vredenburg (2005), innovating for sustainable development is usually ambiguous, i.e. when it is not possible to identify key parameters or when conflicting pressures are difficult to reconcile, such ambiguities make traditional risk assessment techniques unsuitable for GOM. Researchers further argue that sustainability analysis frequently involves a wide range of stakeholders, many of which are not directly involved with the company's production operations activities. Decision makers are thus likely to have significant difficulties in reaching the right decisions if efficient support is not available. Powerful systematic analysis methodologies have great potential in guiding the decision makers to navigate through the complexities and ambiguities (Matos & Hall, 2007). This section reviews the most influential analysis methodologies that could facilitate efficient and effective GOM decision making: life cycle assessment and multi-criteria decision analysis.

2.1 Life cycle assessment

Life cycle assessment or analysis (LCA) is regarded as a "cradle to grave" technique that can support environmentally friendly product design, manufacture and management (Hunkeler et al, 2003; Verghese & Lewis, 2007; Jose & Jabbour, 2010). It can be used to assess the environmental aspects and potential impacts associated with a product, process or a system (Matos & Hall, 2007; Kim et al, 2010). It also allows decision makers to evaluate the type and quantity of inputs (energy, raw materials, etc.) and outputs (emissions, residues, and other environmental impacts, etc.) of production operations in order to completely understand the context involving product design, production, and final disposal (Fuller & Ottman, 2004; Jose & Jabbour, 2010). Standards for the application of LCA have been set up by ISO (International Standards Organisation). A four stage LCA process has been defined (ISO 14040, 1997), as illustrated in Figure 2.

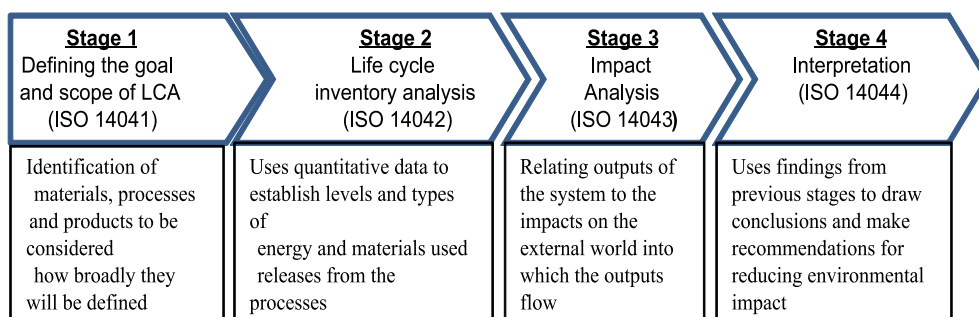| **Stage 1** Defining the goal and scope of LCA (ISO 14041)	**Stage 2** Life cycle inventory analysis (ISO 14042)	**Stage 3** Impact Analysis (ISO 14043)	**Stage 4** Interpretation (ISO 14044)
Identification of materials, processes and products to be considered how broadly they will be defined	Uses quantitative data to establish levels and types of energy and materials used releases from the processes	Relating outputs of the system to the impacts on the external world into which the outputs flow	Uses findings from previous stages to draw conclusions and make recommendations for reducing environmental impact

Fig. 2. Four key stages of LCA process (ISO 14040)

LCA can be conducted along two different dimensions: Product Life Cycle (PLC) and Operational Life Cycle (OLC) analysis. A new product progresses through a sequence of stages from development, introduction to growth, maturity, and decline. This sequence is known as the PLC (Sarkis, 2003; Bevilacqua et al, 2007; Gunendran and Young, 2010). On the other hand, OLC includes stages of procurement, production, packaging, distribution, use, end-of-life disposal and reverse logistics (Nunes & Bennett, 2010). The nature of both of

these analytical tools can generate important insights into environmentally conscious practices in organisations, and there are close interdependencies between PLC and OLC. For example, in the PLC *introduction* phase, procurement is more influential than production for sustainable practices, whilst in the *maturity* and *decline* stages of the PLC, efficient end-of-life and reverse logistics are more influential than distribution operations. It is also not difficult to understand that distribution decisions such as facility locations and modes of transportation will not only influence the forward but also the reverse logistics networks (Bayazit & Karpak, 2007; Chan et al, 2010). However, it is widely acknowledged that environmental methods (LCA in general, PLC and OLC analysis in specific) should be "connected" with social and economic dimensions to help address the 3BL, and that this is only meaningful if they are applied to support decision making process and are not just a "disintegrated" aggregation of facts (Matos & Hall, 2007). It is advantageous that PLC and OLC analysis are conducted to obtain a more holistic picture of the economic and ecological impacts of production operations (Neto, et al, 2010).

2.2 Multi-criteria decision analysis

There is no doubt that GOM decision making has multiple criteria to meet simultaneously, i.e. environmental, social and economic performance objectives. GOM decisions can envelop quantitative, qualitative, tangible and intangible factors. Multi-Criteria Decision Analysis (MCDA) is a generic approach that can empower decision makers to consider all the decision criteria and decision factors, resolve the conflicts between them, and arrive at justified choice. Over the past three decades, several variants of MCDA have been developed. This section compares four widely used MCDA methods: AHP, ANP, fuzzy set theory and fuzzy AHP/ANP.

Analytical Hierarchy Process (AHP) was introduced by Saaty (2005) for solving unstructured problems. Since its introduction, AHP has become one of the most widely used analysis methods for multi-criteria decision making. AHP requires decision makers to provide judgements about the relative importance of each criterion and specify a preference for each decision alternative using each criterion. The output of AHP is a prioritised ranking of the decision alternatives based on the overall performance expressed by the decision makers (Lee, 2009). The key techniques to successfully implement AHP include developing a goal-criteria-alternatives hierarchy, pairwise comparisons of the importance of each criterion and preference for each decision alterative, and mathematical synthesization to provide an overall ranking of the decision alternatives. The strength of AHP is that it can handle situations in which the unique subjective judgements of the individual decision makers constitute an important part of the decision making process (Anderson et al, 2009). However, its key drawback is that it does not take into account of the relationships between different decision factors.

Analytic Network Process (ANP) is the evolution of AHP (Saaty & Vargas, 2006). Given the limitations of AHP such as sole consideration of one way hierarchical relationships among decision factors, failure to consider interaction between various factors and "rank reversal", ANP has been developed as a more realistic decision method. Many decision problems cannot be built as hierarchical as in AHP because of dependencies (inner/ outer) and influences between and within clusters (goals, criteria and alternatives). ANP provides a more comprehensive framework to deal with decisions without making assumptions about the independence of elements between different levels and within the same level. In fact, ANP uses a network without the need to specify levels as in a hierarchy (Sakis, 2003; Dou &

Sakis, 2010) and allows both interaction and feedback within clusters of elements (inner dependence) and between clusters (outer dependence). Such interaction and feedback best captures the complex effects of interplay in sustainable production operations decision making (Gencer & Gurpinar, 2007). Both ANP and AHP derive ratio scale priorities for elements and clusters of elements by making paired comparisons of elements on a common property or criterion. ANP disadvantages may arise when the number of decision factors and respective inter-relationships increase, requiring increasing effort by decision makers. Saaty and Vargas (2006) suggested the usage of AHP to solve problems of independence between decision alternatives or criteria, and the usage of ANP to solve problems of dependence among alternatives or criteria.

Both AHP and ANP share the same drawbacks: (a) with numerous pairwise comparisons, perfect consistency is difficult to achieve. In fact, some degree of inconsistency can be expected to exist in almost any set of pairwise comparisons. (b) They can only deal with definite scales in reality, i.e. decision makers are able to give fixed value judgements to the relative importance of the pair wise attributes. In fact, decision makers are usually more confident giving interval judgements rather than fixed value judgements (Kahraman et al, 2010). Furthermore, on some occasions, decision makers may not be able to compare two attributes at all due to the lack of adequate information. In these cases, a typical AHP/ANP method will become unsuitable because of the existence of fuzzy or incomplete comparisons. It is believed that if uncertainty (or fuzziness) of human decision making is not taken into account, the results can be misleading.

To deal quantitatively with such imprecision or uncertainty, fuzzy set theory is appropriate (Huang et al, 2009; Kahraman et al, 2010). Fuzzy set theory was designed specifically to mathematically represent uncertainty and vagueness, and to provide formalised tools for dealing with the imprecision intrinsic to multi-criteria decision problems (Beskese et al, 2004; Mehrabad & Anvari, 2010). The main benefit of extending crisp analysis methods to fuzzy technique is in its strength that it can solve real-world problems, which have imprecision in the variables and parameters measured and processed for the application (Lee, 2009).

To solve decision problems with uncertainty and vague information where decision makers cannot give fixed value judgements, whilst also taking advantage of the systematic weighting system presented by AHP/ANP, many researchers have explored the integration of AHP/ANP and fuzzy set theory to perform more robust decision analysis. The result is the emergence of the advanced analytical method - fuzzy AHP/ANP (Huang et al, 2009). Fuzzy AHP/ANP is considered as an important extension of the conventional AHP/ANP (Kahraman et al, 2010). A key advantage of the fuzzy AHP/ANP is that it allows decision makers to flexibly use a large evaluation pool including linguistic terms, fuzzy numbers, precise numerical values and ranges of numerical values. Hence, it provides the capability of taking care of more comprehensive evaluations to provide more effective decision support (Bozbura et al, 2007). Details of the key features, strengths and weaknesses of different MCDA methods are compared in Table 1.

2.3 Gap between GOM decision requirements and existing research

Separately, both LCA and MCDA are popular analysis technologies for decision making and sustainable development. The reason why LCA stands out from other eco-efficiency technologies such as Environmental Accounting, Value Analysis and Eco-indicators, is in its capability of highlighting environmental issues from a holistic ("cradle to grave")

perspective. By breaking down the environmental problems into specific issues at different life cycle stages that can be articulated by operations managers, it helps decision makers to explicitly capture, code and implement corresponding environmental objectives in their decision making process. MCDA's main merit is in its competence in handling complex decision situations by incorporating multiple decision criteria to resolve conflicting interests and preferences.

Analysis methods	Key elements	Strengths	Weaknesses	Selected references
AHP	Multi-criteria and multi-attributes hierarchy; Pair wise comparison; graphical representation.	Can handle situations in which decision maker's subjective judgements constitute a key part of the decision making process	Relationships between decision factors are not considered; inconsistency of the pairwise judgements; cannot deal with uncertainty and vagueness	(Saaty, 2005; Anderson et al, 2009)
ANP	Control network with sub-networks of influence	Allows interaction and feedback between different decision factors	Inconsistency of the pairwise judgements; cannot handle situations where decision makers can only give interval value judgements or cannot give values at all	(Saaty & Vergas, 2006; Dou & Sarkis, 2010)
Fuzzy set theory	Mathematical representation; handle uncertainty, vagueness and imprecision; grouping data with loosely defined boundaries.	Can solve real-world decision problems with imprecision variables	Lack of a systematic weighting system	(Beskese et al, 2004; Mehrabad & Anvari, 2010)
Fuzzy AHP/ ANP	Fuzzy membership functions together with priority weights of attributes	Combined strengths of fuzzy set theory and AHP/ANP	Time consuming; complexity.	(Kahraman et al, 2010)

Table 1. Comparison between different multi-criteria decision analysis methods

GOM decisions need to address the 3BL, which undoubtedly require MCDA methods. In the meantime, it is critical that environmental and social concerns be addressed right from the early stage of product and operational life cycles, so that the adverse impact can be minimised or mitigated. Therefore, GOM decision making requires MCDA and LCA to be explored in an integrated rather than isolated manner. By considering both LCA and MCDA technologies together, it could provide decision makers with the vital analysis tools that enable systematic evaluation for improved decision making capabilities. It therefore could allow operations managers to take concerted decisions (and actions as the implementation of the decisions), not only to limit, but also to reverse any long term environmental damage, and thus ensuring that operations activities are undertaken in a sustainable manner.

Despite the urgent requirements from GOM for powerful analysis support, there is little report in the literature discussing the successful integration of both LCA and MCDA

technologies in support of GOM decision making. Next Section of this paper proposes an integrated approach to fill the gap.

3. An integrated sustainability analysis approach

Based on the understanding of the strengths and limitations of different MCDA and LCA methods, this paper proposes an integrated sustainability analysis approach for GOM decision support. The rationality behind the integration approach is that, through integration, LCA will enhance MCDA with the product and operational life cycle stage information so that sustainable operations decision can be made from a more holistic view (through life view), MCDA will enhance LCA with multi-criteria and decision situation information to help pin down stage-specific decision variables and correlations to decision goals and alternatives. The proposed approach comprises two key elements: ANP and OLC analysis. The ANP analysis allows decision makers to address the complexity of decisions situations in sustainable operations. OLC analysis allows decision makers to address the environmental issues across different stages of product's operational life cycle stages. Seamless integration of the ANP and OLC analysis is enabled through immediate sharing of consistent information about the GOM decision context and content.

3.1 Performing OLC analysis to understand decision problems from life cycle perspective

During the OLC process – procurement, production, distribution, use, end-of-life treatment and reverse chain, different green issues need to be addressed at different stages. Therefore environmental objectives may be defined in different forms for GOM decision making. For example, greener material selection at *procurement* stage, cutting down greenhouse gas emission at *production* stage, or reducing energy consumption at the *use* and *distribution* stages, and safe waste management for *end-of-life* treatment, and product recovery through *reverse logistics*. Figure 3 illustrates more comprehensive environmental objectives used at different OLC stages for green operations decision making.
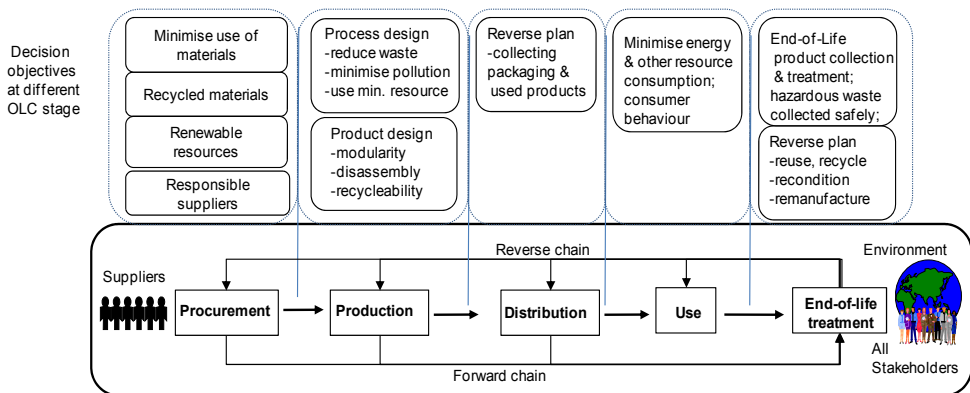

Fig. 3. OLC analysis for GOM

In sustainability analysis, decision objectives can be instantiated by using appropriate indicators (OECD, 1991; Bell & Morse, 1999). An indicator expresses one or more

characteristics that can be empirically observed or calculated. An indicator aims at identifying those aspects of phenomenon that are considered to be important as for monitoring and control. Therefore, it is a piece of information that refers to an intrinsic attribute or to a set of attributes of the phenomenon or associated to other phenomena closely related to the former. In GOM, indicators are usually described with reference to the three principal sustainability dimensions. For example, environmental indicators include greenhouse gas emissions, quantity of wastes, etc. Social indicators can be unemployment rate and crime level etc. While economic indicators include GDP, inflation rate and so on. Researchers have recognised that it is the system of indicators rather than individual indicators that is more significant for GOM (Bottero et al, 2007). Although made up of individual indicators, the system of indicators can describe and give inter-correlated information from a logical and functional view. The proposed integrated sustainability analysis approach in this paper explores a system of indicators.

3.2 Development of decision network models with ANP

In order to address the decision making challenges for GOM from an holistic perspective, it is extremely important:

1. To identify the relationships between the key components in a sustainable operations system: operations strategy, operations structural and infrastructural decisions, environmental issues and social issues. The relationships should be based on the understanding of the contents of each component. For example, how environmental issues such as waste management, reduce-reuse-recycle, and pollution control can be addressed by operations strategies and its structural and infrastructural decisions. Similarly, how social issues such as staff and customer safety, employment policy, workplace stress, price manipulation, honesty and transparency of supplier relationships can be addressed by the operations strategies and decisions;

2. To define operations decision hierarchy/network, i.e. the dependency between operations strategic decisions, structural decisions and infrastructural decisions. Within the decision network, if decision on one network node changes, what are the decision propagation paths along the network and consequences to other decisions? What needs to be done to manage the decision changes?

To address the above issues and to make sure multiple criteria including environmental and social objectives from the OLC analysis (Section 3.1) are integrated into the decision making process, Analytic Network Hierarchy (ANP) technology has been explored. The result of the process is a GOM analytical model consisting of a control hierarchy, clusters and elements, as well as interactions between clusters and elements. Six key steps have been undertaken to develop the GOM analytical model.

Step 1. specify decision goal based on the OLC analysis of the GOM decision problem, and define decision criteria clusters, sub-criteria and detail criteria.

Step 2. design alternatives for the specific GOM decision problem. It is advised that adopting alternatives from "good practices" in the filed and using preliminary elimination increases the quality of decision alternatives.

Step 3. determine the network structure and interactions. The output of this step will be a control hierarchy, as shown in Figure 4. It should be noted that in the Figure the influence between the elements are bi-directional, which means that the importance of the criteria influences the importance of the alternatives, and vice versa.
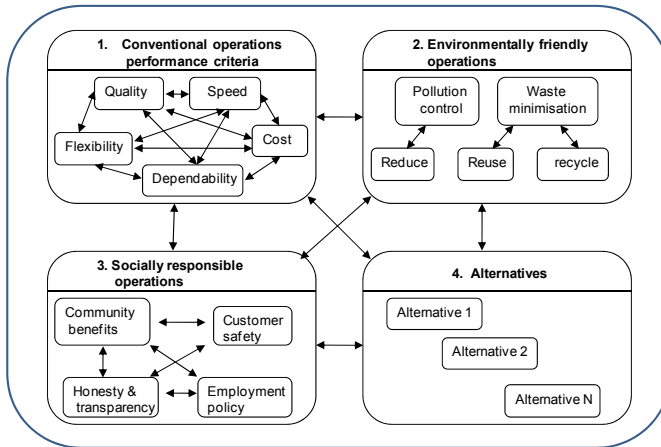
Fig. 4. The GOM ANP network control hierarchy

Step 4. create a super-matrix based on the network control model from step 3. The super-matrix is composed of ratio scale priority vectors derived from pair-wise comparison matrices. The super-matrix structure is shown as follows:

$$
W = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \end{array} \begin{bmatrix} w_{11} & w_{12} & w_{13} & w_{14} \\ w_{21} & w_{22} & w_{23} & w_{24} \\ w_{31} & w_{32} & w_{33} & w_{34} \\ w_{41} & w_{42} & w_{43} & 0 \end{bmatrix}
\begin{array}{cccc} 1 & 2 & 3 & 4 \end{array}
$$

In the above equation, subscript number 1 shows the criteria cluster belonging to conventional operations performance objectives; subscript number 2 shows the criteria cluster belonging to environmental friendly operations; subscript number 3 shows the criteria cluster belonging to socially responsible operations; subscript number 4 shows the criteria cluster belonging to alternative operations. In the super-matrix, w_{11}, w_{12}, w_{13}, and so on represent the sub-matrices. The cluster which has no interactions is shown in the super-matrix with a value of zero. Those non-zero values mean that there are dependencies between the clusters. For example, w_{12} means that cluster 1 depends on cluster 2. Similar to that in AHP, the 1 – 9 scale system developed by Saaty (Saaty & Vargas, 2006) is used in this research, and pairwise comparisons are made to create the super-matrix.

Step 5. yield the weighted super-matrix. The un-weighted super-matrix from step 4 must be stochastic to obtain meaningful limiting results. This step is to transform the un-weighted into a weighted super-matrix. To do this, firstly the influence of the clusters on each other is determined, which generates an eigenvector of the influences. Then the un-weighted super-matrix is multiplied by the priority weights from the clusters, which yields the weighted super-matrix.

Step 6. stabilise the super-matrix. This step involves multiplying the weighted super-matrix by itself until the row values convergence to the same value for each column of the matrix.

By the end of step 6, the limiting priorities of all the alternatives should be computed and shown in the matrix. The alternative with the highest priority should become transparent and will become the optimal choice to decision makers.

3.3 The integration of OLC analysis and ANP

In order to provide efficient support for holistic decision making in GOM, decision requirements need to be met to address multiple criteria across OLC stages. As shown in Figure 5, information about decision criteria and indicators derived from the OLC analysis empowers decision makers to target the most important environmental issues from a life cycle perspective, so that adverse impact of decisions from one stage to another can be minimised and mitigated. ANP addresses multiple decision criteria by incorporating decision makers' preferences and score their judgement within the ANP pair-wise comparison matrices. The dependence between multiple criteria is taken into account through the ANP network interactions. By integrating ANP and OLC analysis, efficient decision support will be provided for holistic decision making to be made to address multiple decision criteria throughout operational whole life cycle.
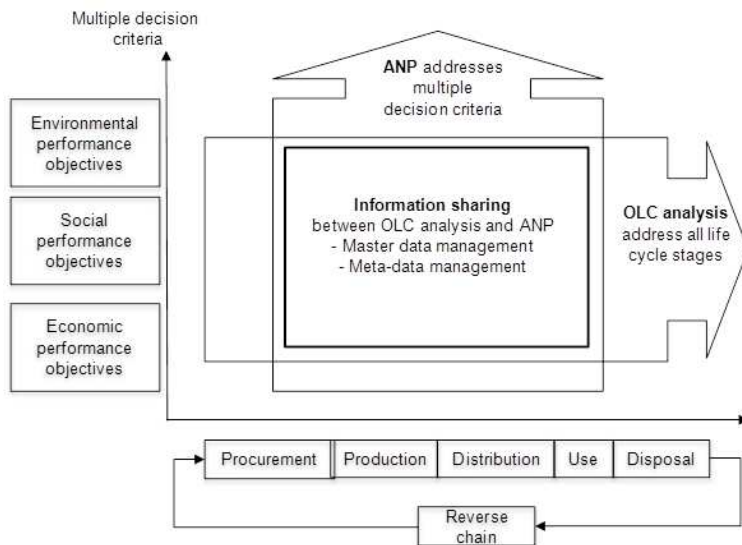

Fig. 5. Integration of OLC analysis and ANP

By integrating the information about the interactions among the three main sustainability dimensions and their cause-effect relations in the OLC analysis and ANP, it allows decision makers to measure the interconnections and the influences both horizontally (across multiple decision criteria) and vertically (across life cycle stages), which provides an integrated approach for the sustainability analysis for holistic decision making in GOM. Two strategies have been explored for the information integration between OLC analysis

and ANP model development: one is through master data management, and the other is through meta-data management.

In a GOM decision support system, master data is a very important concept which supports data integrity and consistence. Master data are persisted, long lived data which need to be stored centrally. They can be used by all business functional units and at all levels of organization (Monk & Wagner, 2009). Examples of master data in an operations system are material master, vendor/supplier master, and customer master records. Additionally, master data also includes hierarchies of how individual products, customers and accounts aggregate and form the dimensions which can be analyzed. Master data management is carried out to ensure that material master, vendor/ supplier master and customer master for example are consistently stored and maintained, so that all information users, both people (including decision makers) and computer systems, can access the right information at all times.

As the demand for business intelligence grows, so do the available data sources, data warehouses, and business reports that decision makers depend on for business decisions. While master data management can be used to effectively integrate business data across business functions, metadata management provides an extra layer of reliability when GOM decision support systems use multiple data sources. Separate departmental deployments of business solutions (resulting from being in charge of different OLC stages) have inevitably created information silos and islands, which makes it significantly more difficult to manage the information needed to support holistic decision making. This is especially the case where the data sources change, which will have significant impact on the GOM decisions. Decision makers will also tend to put various trust in the available information with various origins. Metadata management can provide powerful support for data traceability and give decision makers essential assurance of the integrity of information on which their decisions are based. A generic definition of metadata is "data about data" (Babin & Cheung, 2008). In green operations management, typical use of metadata has been identified as helping to provide quick answers to the questions such as: What data do I have? What does it mean? Where is it? How did it get there? How do I get it? And so on. The answers to these questions will have a profound impact on the decisions to be made.

4. Application of the integrated approach to case study

This section discusses the application of the proposed integrated sustainability analysis approach to a case example from Plastics Manufacturing industry.

4.1 The case

Manufacturing industry is, without a doubt, a major contributor to world's economy (e.g. GDP growth). At the same time, manufacturing has been in the centre of the root cause for environmental issues. Along with the wave of business globalisation, more and more social problems are being unfolded from the manufacturing industry. It is a common acknowledgement that the quicker to take effective means to tackle the environmental and social problems caused by manufacturing industry, the better (Nunes & Bennet, 2010). As one of the fastest developing countries on the planet, China has been branded as the world's manufacturing workshop in recent years. Its adverse impact on 3BL sustainability can no longer be ignored. According to a 1998 report of the World Health Organisation, of the ten most polluted cities in the world, seven were in China and the situation has not changed

much (Chow, 2010). Therefore, Chinese manufacturing industry can provide perfect cases for researchers to study the GOM issues. This paper looks at a case from a Chinese Plastics Manufacturing company.

One of the most influential products from Plastic Manufacturers is plastic bags. Highly convenient, strong and inexpensive, plastics bags were appealing to business and consumers as a reliable way to deliver goods from the store to home. However, many issues associated with the production, use and disposal of plastic bags may not be initially apparent to most users, but now are recognised extremely important and need to be addressed urgently. By exploring the integrated OLC and ANP approach with the case study, this paper aims to help decision makers achieve better understanding of the full ecological footprint of the products, and to provide efficient decision support in dealing with the associated negative impacts on environment and social equity.

4.2 Eliciting decision criteria and indicators through OLC

It was recognised that the Plastic Manufacturing company needs to understand plastics bags life cycle impacts by undertaking streamlined OLC to elicit environmental indicators. The information can then be used to enlighten operations managers and help them make informed decisions. From the manufacturer's viewpoint, planning ahead ensures that any potential risks to business are anticipated whenever possible. A key benefit is that a proactive approach is likely to be more scientifically sound than a reactive approach, which is merely responding to government legislation or consumer concerns.

Figure 6 demonstrates the application of LCA to plastic bags, with energy inputs and emission output at each key stage of the life cycle. In terms of waste management, three potential strategies can be implemented: to make recyclable bags, reusable bags and degradable bags. Specific indicators for environmentally friendly operations obtained from the OLC process include minimum energy consumption, gas emission, and land and water pollution. Indicators for socially responsible operations include minimum damage/ threat to human health, wildlife and tourism etc.
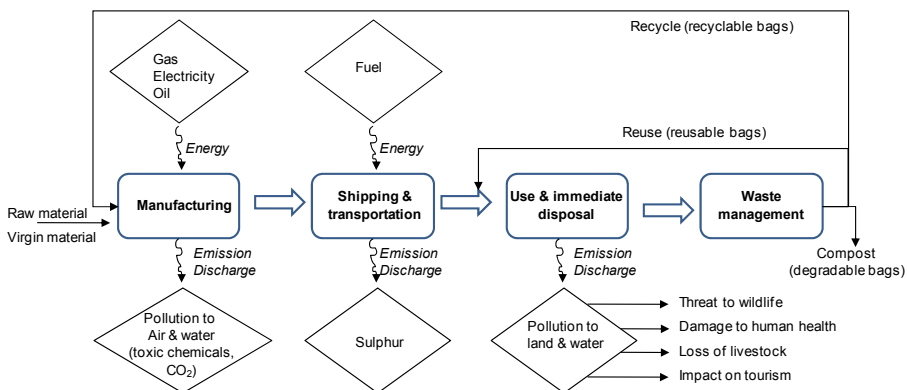

Fig. 6. OLC analysis for plastic bags

4.3 Developing the GOM analytical model and results

Plastic grocery bags were first introduced to Chinese supermarkets over 30 years ago. Today, 80 percent of grocery bags are plastic (FMI, 2008). To address the environmental and

social issues resulting from plastic bags, many crucial decisions that plastic manufacturer needs to make during the whole life-cycle. Four decision alternatives can be derived from the OLC analysis:

1. To make *recyclable* plastic bags. This alternative seems to be taken at rather late stage of the life cycle, but corresponding considerations are required at early stages such as in the material selection stage so that recyclable plastic bags can be sorted into proper categories and processed later.
2. To make *reusable* plastic bags. This alternative requires appropriate actions to be taken at early stages of the life cycle. For example, at the material selection and manufacturing stages, appropriate considerations should be taken so that the reusable bags have the strengths to be reused for a certain number of times.
3. To make *degradable* plastic bags, such as those which degrade under micro-organisms, heat, ultraviolet light, mechanical stress or water.
4. To replace plastic bags with *paper* bags. For some time, manufacturers were forced to make a key decision – "plastic or paper". Research clearly showed that paper shopping bags make a much larger carbon footprint from production through recycling. For example, a paper bag requires four times more energy to produce a plastic bag. In the manufacturing process, paper bags generate 70 percent more air and 50 times more water pollutants than plastic bags (FMI, 2008).

4.3.1 Development of the network control hierarchy for the Plastic Bags case

The generic ANP models discussed in Section 3 include comprehensive factors of GOM decision situations, this Section applies the GOM analytical models to a customised situation of dealing with the Plastic Bags. Therefore, a simplified version of the generic ANP Control Hierarchy for the case has been developed, as shown in Figure 7. The analytical models discussed in the case study were developed using Super Decisions® software. As can be seen from the Figure 7, the GOM network consists of four clusters. Each cluster has one or more elements that represent the key attributes of the cluster. Elements for Clusters 2, 3 and 4 have derived from the case OLC process (Section 4.2). Connections between the clusters indicate the influence and dependency. A reflexive relationship on a cluster in the model (such as the one for Cluster 2) means that there is inter-dependency between the elements in the same cluster.

4.3.2 Pair-wise comparisons for the Plastic Bags case

In complex decision making using ANP, a series of pair-wise comparison are made to establish the relative importance of the different clusters and elements with respect to a certain component of the network, including clusters comparison and elements (of the clusters) comparison. Both cluster and element comparisons are based on a ratio scoring system.

In the pair-wise comparison process for the Plastic Bags case, a 9-scale ratio scoring system suggested by Saaty (2005) has been employed. A judgment or comparison is the numerical representation of a relationship between two elements that share a common parent. Each judgement reflects the answers to two questions: which of the two elements is more important with respect to a higher level criterion, and how strongly, using the 1—9 scale shown in Table 2. At the level of clusters comparison, there are four 4x4 matrices containing the judgements made pairwise comparisons established from the survey and discussion with groups of
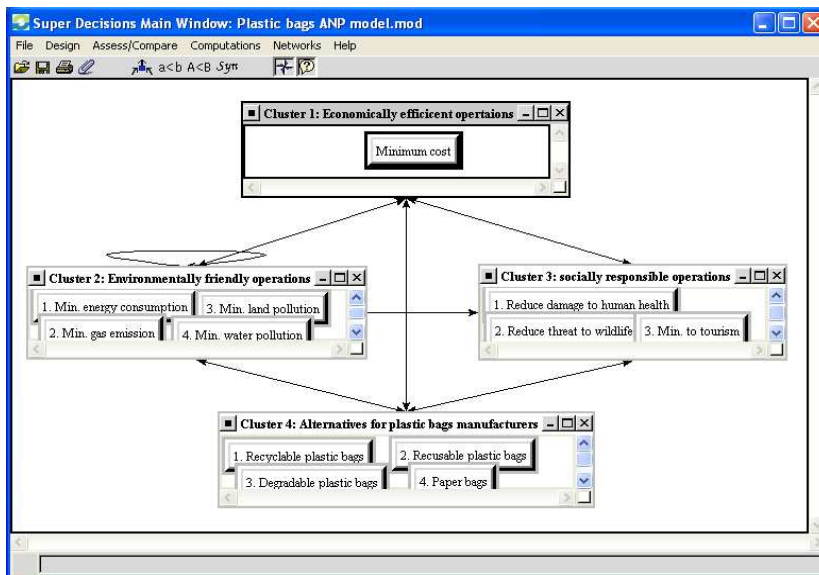
Fig. 7. GOM network control hierarchy for the Plastic Bags case

Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favour one activity over another
5	Strong importance	Experience and judgment strongly favour one activity over another
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	For compromise between the above values	Sometimes one needs to interpolate a compromise judgment numerically because there is no good word to describe it.
Reciprocals of above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A comparison mandated by choosing the smaller element as the unit to estimate the larger one as a multiple of that unit.
Rationales	Ratios arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix
1.1-1.9	For tied activities	When elements are close and nearly indistinguishable; moderate is 1.3 and extreme is 1.9.

Table 2. The Fundamental Scale (Saaty, 2005)

experts of sustainability assessment. The pairwise comparison matrices at this level allow decision makers to evaluate the relationships existing between the different sustainability

aspects, i.e. economic, environmental and social. For example, Table 3 represents the comparison among the four clusters from the point of view of socially responsible operations. The priority vectors are calculated and shown in the last column of the Table.

Social sustainability	Alternatives	Environmental sustainability	Economic sustainability	Social sustainability	Priority vector
Alternatives	1	7	5	3	0.740430
Environmental sustainability	1/7	1	3	1/3	0.168434
Economic sustainability	1/5	1/3	1	1/5	0.091136
Social sustainability	1/3	3	5	1	0

Table 3. Pairwise cluster comparison matrix with respect to the social sustainability

When the priority vectors for all four clusters are calculated and aggregated in one table, a Cluster Matrix is formulated for the Plastic Bags case, as shown in the Figure 8. The Cluster Matrix is used later to transform super-matrix from unweighted to weighted format.

Cluster Node Labels	Cluster 1: Economic objectives	Cluster 2: Environmental objectives	Cluster 3: Social objectives	Cluster 4: Alternatives
Cluster 1: Economic objectives	0.000000	0.077381	0.091136	0.539616
Cluster 2: Environmental objectives	0.195970	0.108877	0.168434	0.296962
Cluster 3: Social objectives	0.145885	0.309332	0.000000	0.163423
Cluster 4: Alternatives	0.658145	0.504410	0.740430	0.000000
Done				

Fig. 8. Cluster matrix

Once the clusters comparisons are done, it is essential to perform the pairwise comparisons at more detailed level, i.e. comparisons between elements (of the clusters). The element comparisons can be done in similar manner as for the cluster comparisons.

4.3.3 Super-matrix formation and global priorities for the Plastic Bags case

The result of all pairwise comparisons is then input for computation to formulate a super-matrix. In the Plastic Bags case, three different super-matrices have been generated: a Un-weighted, a Weighted super-matrix and a Limit Super-matrices. Super-matrices are arranged with the clusters in alphabetical order across the top and down the left side, and with the elements within each cluster in alphabetical order across the top and down the left side. An Un-weighted Super-matrix contains the local priorities derived from the pair-wise

comparisons throughout the network. Figure 9 shows part of the Un-weighted matrix for the Plastic Bags case (because of the space limit, part of the super-matrix is hidden. In the real software environment, the whole super-matrix can be seen by scrolling the bars on the interface).

Super Decisions Main Window: Plastic bags ANP model.mod: Unweighted Super Matrix

Cluster Node Labels		Cluster 1: Economic objectives	Cluster 2: Environmental objectives				Cluster 3: Social objectives		
		1.1 Minimum cost	2.1 Min. energy consumption	2.2 Min. gas emission	2.3 Min. land pollution	2.4 Min. water pollution	3.1 Reduce damage to human health	3.2 Reduce threat to wildlife	3.3 Min. to tourism
Cluster 2: Environmental objectives	2.4 Min. water pollution	0.166231	0.333333	0.414370	0.333333	0.000000	0.250000	0.250000	0.250000
Cluster 3: Social objectives	3.1 Reduce damage to human health	0.728584	0.412602	0.738308	0.333333	0.333333	0.000000	0.000000	0.000000
	3.2 Reduce threat to wildlife	0.162579	0.259921	0.170172	0.333333	0.333333	0.000000	0.000000	0.000000
	3.3 Min. to tourism	0.108836	0.327477	0.091519	0.333333	0.333333	0.000000	0.000000	0.000000
Cluster 4: Alternatives	4.1 Recyclable plastic bags	0.085499	0.616119	0.137534	0.250000	0.250000	0.250000	0.250000	0.250000
	4.2 Recusable plastic bags	0.384785	0.193562	0.198511	0.250000	0.250000	0.250000	0.250000	0.250000
	4.3 Degradable plastic bags	0.373530	0.085835	0.370114	0.250000	0.250000	0.250000	0.250000	0.250000
	4.4 Paper bags	0.156186	0.104485	0.293841	0.250000	0.250000	0.250000	0.250000	0.250000

Done

Fig. 9. The Un-weighted Super-matrix for the Plastic Bags case

The Unweighted Supermatrix has to be transformed into the Weighted Supermatrix. The transformation process involves multiply the Unweighted Supermatrix by the Cluster Matrix, so that the priorities of the clusters can be taken into account in the decision making process. The Weighted Supermatrix for the Plastic Bags case in shown in Figure 10.

However, the Weighted Supermatrix is very difficult for decision makers to use because of the distribution of vector values. This requires conducting a finishing touch in the GOM analytical model development process by transforming the Weighted Supermatrix into a Limit Supermatrix. The Limit Supermatrix is obtained by raising the weighted supermatrix to powers by multiplying itself. When the column of numbers is the same for every column, the Limit Supermatrix has been reached and multiplication process is halted. The Limit Supermatrix for the Plastic Bags case is shown is Figure 11. A graphical overview of the Limit Supermatrix of the case is shown in Figure 12, in which the consequence of all alternatives is more visualised.

Based on the Limit Super-matrix results and their visual representation shown in the Figures 11 and 12, recommendation of the decision alternatives can be drawn as follows:

1. Paper bags as a replacement of plastic bags is the least ideal choice, based on evidence from the super-matrix: a paper bag requires more energy than a plastic bag (in the super-matrix, alternative 4 Paper bags contributes a lot less to objective 2.1 Minimum energy consumption); in the manufacturing process, paper bags generates a lot more air and water pollutions than plastic bags (in the super-matrix, alternative 4 Paper bags contributes a lot less to objectives 2.2 and 2.4); paper bags also take up more landfill space.

2. Plastic bags recycling is not a preferred choice in terms of achieving economic, the cost, objective.
3. Making degradable bags is a relatively ideal choice (with an overall value of 0.98 in the Figure 12).
4. Making reusable bags is the preferred choice because it has the highest overall score based on the data collected from the company.

Cluster Node Labels		Cluster 1: Economic objectives	Cluster 2: Environmental objectives				Cluster 3: Social objectives		
		1.1 Minimum cost	2.1 Min. energy consumption	2.2 Min. gas emission	2.3 Min. land pollution	2.4 Min. water pollution	3.1 Reduce damage to human health	3.2 Reduce threat to wildlife	3.3 Min. to tourism
Cluster 2: Environmental objectives	2.4 Min. water pollution	0.032576	0.036292	0.045115	0.036292	0.000000	0.042109	0.042109	0.042109
Cluster 3: Social objectives	3.1 Reduce damage to human health	0.106290	0.127631	0.228383	0.103111	0.103111	0.000000	0.000000	0.000000
	3.2 Reduce threat to wildlife	0.023718	0.080402	0.052640	0.103111	0.103111	0.000000	0.000000	0.000000
	3.3 Min. to tourism	0.015878	0.101299	0.028310	0.103111	0.103111	0.000000	0.000000	0.000000
Cluster 4: Alternatives	4.1 Recyclable plastic bags	0.056271	0.310776	0.069373	0.126102	0.126102	0.185107	0.185107	0.185107
	4.2 Recusable plastic bags	0.253244	0.097634	0.100131	0.126102	0.126102	0.185107	0.185107	0.185107
	4.3 Degradable plastic bags	0.245837	0.043296	0.186689	0.126102	0.126102	0.185107	0.185107	0.185107
	4.4 Paper bags	0.102793	0.052703	0.148216	0.126102	0.126102	0.185107	0.185107	0.185107

Fig. 10. The Weighted Super-matrix for the Plastic Bags case

Cluster Node Labels		Cluster 1: Economic objectives	Cluster 2: Environmental objectives				Cluster 3: Social objectives		
		1.1 Minimum cost	2.1 Min. energy consumption	2.2 Min. gas emission	2.3 Min. land pollution	2.4 Min. water pollution	3.1 Reduce damage to human health	3.2 Reduce threat to wildlife	3.3 Min. to tourism
Cluster 1: Economic objectives	1.1 Minimum cost	0.239251	0.239251	0.239251	0.239251	0.239251	0.239251	0.239251	0.239251
Cluster 2: Environmental objectives	2.1 Min. energy consumption	0.068682	0.068682	0.068682	0.068682	0.068682	0.068682	0.068682	0.068682
	2.2 Min. gas emission	0.037753	0.037753	0.037753	0.037753	0.037753	0.037753	0.037753	0.037753
	2.3 Min. land pollution	0.050458	0.050458	0.050458	0.050458	0.050458	0.050458	0.050458	0.050458
	2.4 Min. water pollution	0.055038	0.055038	0.055038	0.055038	0.055038	0.055038	0.055038	0.055038
Cluster 3: Social objectives	3.1 Reduce damage to human health	0.089553	0.089553	0.089553	0.089553	0.089553	0.089553	0.089553	0.089553
	3.2 Reduce threat to wildlife	0.039768	0.039768	0.039768	0.039768	0.039768	0.039768	0.039768	0.039768
	3.3 Min. to tourism	0.034119	0.034119	0.034119	0.034119	0.034119	0.034119	0.034119	0.034119

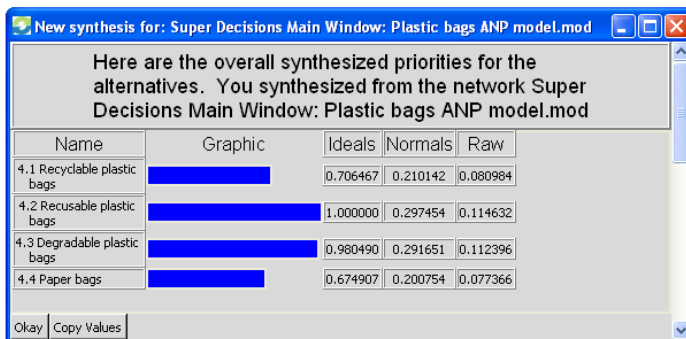Fig. 11. The Limit Super-matrix for the Plastic Bags case

Fig. 12. Visualised representations of the global priorities of the four alternatives

5. Discussion and conclusions

The focus of the paper is on an integrated sustainability analysis for the holistic decision making in GOM. The approach integrates two core elements: an Operational Life Cycle (OLC) assessment, and Analytic Network Process (ANP) for multi-criteria decision analysis. At different stages of OLC (procurement, production, distribution, use, and reverse logistics), GOM has different strategic focus. Understanding the OLC influence on operations foci, the environmental and social sustainability issues can be better addressed in the operations decision making process.

The strengths of the integrated approach lies in that information about decision objectives and indicators derived from the OLC analysis is directly fed into the GOM analytical model development, which allows decision makers to find the optimal solution to decision problems to achieve the multiple sustainability criteria. At its highest level, GOM decision criteria include economic, environmental and social objectives. Within each of the three areas, more specific criteria have been generated from the OLC analysis. For example, economic criteria are further broken down to cost reduction, high margin, productivity improvement, maximum profit etc. Environmental sustainability includes such criteria as waste minimisation, reduce-reuse-recycle, and pollution control. Social criteria are based on labour, discrimination, mistreatment, health and safely, working hours, minimum wages etc. For operations decision making across multi-stages of OLC, there can be a huge number of decision variables and decision alternatives for each decision problem. Under such complex decision situations, GOM analytical models allow operations managers to weigh the importance of each criterion, to rate the satisfaction level of each decision alternative, to calculate aggregated score for decision choices against criteria, and to predict the consequence of each alternative (Sarkis, 2003). Therefore managers can confidently and transparently perform "what-if" and sensitivity analysis for each decision option, subsequently improve their judgements and make informed decisions. The novelty of the integrated approach is augmenting the ANP by OLC analysis so that life cycle stage impact on the green operations decisions is coherently incorporated.

The benefit of the integrated sustainability analysis approach is that it provides a formal, evidence-based justification for operations decisions that integrates environmental, social and economic sustainability objectives into operations manager's proactive decision making process. Therefore, environmental and social values are not just talked (in words) but also enacted (in actions).

The evaluation of the integrated sustainability analysis approach has been illustrated through a decision case from the plastic manufacturing industry. The case study shows that the approach has great potential in providing scientific evidence to support GOM decision making under complex situations and with multiple decision criteria.

Limitations of the approach include:

- It is developed for and evaluated in production operations case. Its applicability to service operations needs further exploration.
- At this stage, the research has not considered feedback of clusters to the decision support system yet. Further work needs to explore a mechanism and tool to manage the feedback.

6. Acknowledgement

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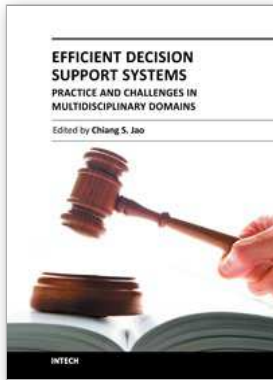
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