THE UNIVERSITY OF HULL

Environmental Risk Management System Design for Hazardous Waste Materials

being a Thesis submitted for the Degree of Doctor of Philosophy,

Department of Engineering

in the University of Hull

by

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August 2012

Acknowledgements

Above all, the author would express sincere thanks to the “Hull-China Research Joint Scholarship” for the sufficient funding throughout three years’ PhD study. I am indebted to the both sponsors, University of Hull and China Scholarship Council, respectively. I would like to thank the Department of Engineering, for the support throughout my whole PhD. Thanks especially gives to the Head of Department, Dr. James Gilbert, for his patience and time to assess this thesis.

Secondly, I would express my gratitude to my first supervisor, Dr. Gareth Neighbour, who has leaded me into this research, for his encouragement and inspiration. I am also grateful to my second supervisor, Dr. Pauline Deutz, for her generous contribution and useful discussion of my PhD progressing.

Thanks in addition go to my esteemed colleague, Dr. Michael McGuire, for his generous help as always, not only the useful comments on my PhD study, but also meticulous checking on my English writing and presenting skills. And thanks also give to my other colleagues, Mr. Gary Kipling. Due to their kind help and support, I consider myself to love settled down for PhD research very easily and work fortunately in such a friendly, harmonious environment.

I wish to give the most especial gratitude to my parents for their selfless dedication, great efforts without any complaints, never-endless care and encouragement during my long time study. I really cannot thank them enough.

The author wishes to thank all his friends around the world, for their generous care, support and encouragement, especially to Ms. Jiaojie Han, who helps me make breakthrough in a new background for my PhD study, and to Ms. Alina Lin for her continuous encouragement, generous help and useful discussion.

At last but not least, I would like to express my sincere thanks to my Chinese Alma Mater, Southwest Jiaotong University, Chengdu, especially the ‘School of Environmental Science and Engineering’ for their cultivation. In particular, thanks should be given to my Master Supervisor, Professor Dan Liu and Professor Tao Huang, for their continued caring and support.

Abstract

Hazardous materials can be generally deemed as any material which, because of its quantity, concentration, or physical, chemical, or infectious characteristics, may cause, or pose a substantial or potential hazard to human health or the environment. In the context of "sustainable development", most 'materials' could be deemed to be 'hazardous' at some stage of their lifecycle, *i.e.* from extraction to final disposal.

This PhD study develops a decision support system for engineers and policy makers to help limit environmental burden, by reducing the environmental risk and the associated carbon footprint, from the perspective of 'hazardous' materials in product design, through the application of 'game theory' and 'grey theory' *etc*, as well as various computational approaches, by helping the designer identify novel solutions or mitigation strategies.

The thesis starts by introducing the problem situation of the study and identify the research objectives, as well as previous studies have been reviewed in order to set this study in context.

Since it is evident that consumers drive the open market, and their preference may be influenced by the carbon footprint label of products, the decision support system proposes an improved carbon labelling scheme to demonstrate the significance of a

product's carbon footprint in a more visual way. The prototype of the scheme is derived from the concept of 'tolerability of risk', providing a framework by which judgments can be made as to whether society will accept the risk from hazardous materials.

Application of game theory for decision support is a novel approach in this study, which aids decision-making by selecting appropriate strategies for both organisations and policy makers to reduce environmental impact. In this context, a game between manufacturers and government in the field of clean production is generated with various game scenarios to reflect the variation trend of strategic actions, and then developed to discuss the reduction of the inherent risk posed by 'hazardous' materials and carbon emissions on the supply chain network.

The 'hierarchy of waste' suggests that the most preferable state for sustainability is prevention or the elimination of waste. Although this is not wholly practicable in real terms, the framework gives the importance to waste minimisation and prevention, especially promotes the cleaner production. In addition to strategy selection for mitigating environmental impact, the decision support system also develops an evaluation methodology for application by engineers to aid decision-making on materials selection, thus to improve the materials performances, promote cleaner production and provide better and sustainable products for public consumption.

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Chapter 1: Introduction

1.1 Background

Within the United Kingdom, approximately 272 million tonnes of waste from households, commerce and industry is generated annually (DEFRA, 2007). In most cases, waste materials treatment appears to be relatively straight forward and in many cases results in disposal to landfill. Fig.1.1 shows the current situation of waste materials disposal to landfill in European countries, where United Kingdom (UK) lags some way behind and maintains the higher landfill rate (DEFRA, 2007). However, this is relatively simplistic since most, but not all materials can be considered harmful or 'hazardous' to the environment to a greater or larger extent. That is to say most materials sent to landfill have an environmental impact.

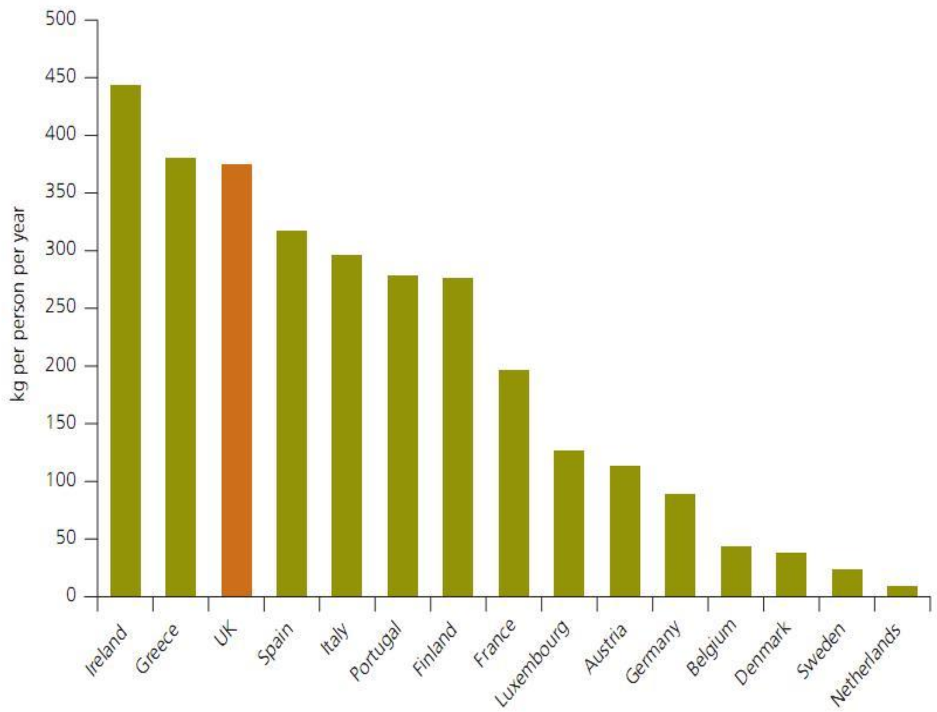

Fig.1.1. Municipal waste materials sent to landfill (adopted from: DEFRA, 2007)

The definition of hazardous materials, as given by Lee (2005) is "*anything which, because of its quantity, concentration, or physical, chemical, or infectious characteristics may cause, or significantly contribute to, an increase in mortality; or cause an increase in serious irreversible, or incapacitating reversible, illness: or pose a substantial present or potential hazard to human health and the environment when improperly treated, stored, transported, or disposed of, or otherwise managed*". Examples are the leaching properties of common polymers in the food supply chain, or formaldehyde, a common substance used in some furnishings, which is deemed to be carcinogenic. Thus, given this broad definition, the implication is that there are very few manufactured materials that would not be considered hazardous to some degree if badly managed or disposed of inappropriately. It follows that there is a need to consider the environmental risk to society associated with everyday consumer products. The environmental risk which is caused by the 'hazardous' materials can be deemed as a measure of probability that damage to life, health, property, and/or the environment will occur as a result of a given hazard (Lee, 2005). Therefore, the risk to the environment resulting from 'hazardous' materials as defined here, and the attendant health implications, need to be carefully assessed in the context of the product life-cycle. Furthermore, it is now widely acknowledged that our assessment of risk is often highly subjective, and that society tolerates a given level of risk on the basis of the perceived benefits and/or associated hazards (McGuire and Neighbour, 2010).

With natural resources being exploited at an increasing rate, as well as the threat of "climate change", the concept of Sustainable Development has been given more and more attention. Sustainable Development is now broadly recognized as *"the principles of the current process of economic and technological development to ensure that the use of environmental resources to satisfy present demands is managed in a way that they are not left so damaged or impoverished they cannot be used by future generations"* (WCED, 1987). In this context, all materials can be seen as 'hazardous' in certain situations or at the various stages of the product lifecycle (Giudice, Rosa and Risitano 2006), *i.e.* design, production, transportation, use, and final disposal. In particular, hazardous materials perhaps convert into the hazardous waste at the post consuming stage. In addition to the immediate risk posed by 'hazardous' materials, it is also important in the socio-political context to attach importance to the 'carbon footprint[1]', which may be an increasingly used indicator of environmental sustainability. Fossil fuels such as petrol, diesel *etc*. have been widely consumed during production and transportation, resulted in methane or other greenhouse gas generation. Due to most of the waste materials, *i.e.* organic materials, ultimate ending up in landfill, landfill gas, if uncontrolled, is considered as one of the main sources of greenhouse gas emissions. Thus, not only reducing, reusing and recycling waste materials, but also providing better, safer and sustainable products for public consumption, should be significant indicators in the goal of achieving sustainable development.

[1] which is interpreted as the total amount of carbon dioxide emitted, or its equivalent in terms of other greenhouse gases emissions (Carbon Trust, 2006)

1.2 The problem situation

With regard to the ‘sustainable development’, how to achieve sustainability becomes a worldwide concern. Thus, the ‘Triple Bottom Line’ has been put forward to measure the impact of an organisation’s activities (Henriques and Richardson, 2004). Table 1.1 shows that the Triple Bottom Line (TBL) has reflected a company’s value in terms of three dimensions, including not only its financial performance, *i.e.* profitability, but also the environmental and social resources (Savitz and Weber, 2006). Thus, a sustainable business should not only focus on the economic prosperity, but also pay much more attention to the environmental and social perspectives, ultimately to benefit all the stakeholders who will be affected by these three dimensions.

Table 1.1 Triple bottom line (Reproduced from Savitz and Weber, 2006)

Economic performance	Environmental performance	Social performance
Profitability	Air quality (CO_2 emissions)	Human rights
Return on investment	Water quality	Community impacts
Tax payment	Waste production and energy consumption	Product responsibility

However, it is thought that manufacturers, depending upon their business strategy, will tend to focus primarily on their owned economical profit and thus would be reluctant to bear the additional economic cost for technological innovation to implement ‘cleaner production’. It is often assumed that manufacturers neglect their higher moral responsibility to provide ‘environmentally sound’ products having due regard to the Triple Bottom Line. For instance, product design typically still does not consider the full lifecycle, especially giving little deliberation in the post-consuming stage (Deutz, Neighbour and McGuire, 2010). To provide ‘better’ and ‘safer’ products for the public as well as achieve the long term commercial sustainability, it is the duty of government to regulate the production process to ensure ‘safe’ products not only in use to reduce their inherent risk, but also to mitigate the environmental impact. The question is whether the governmental regulation is sufficient and whether manufacturers would be willing to bear the additional cost for green technological innovation.

In addition to environmental education sponsored by government, consumers’ preference may be also influenced by the introduction of ‘carbon labelling’ scheme, which has the potential to stimulate reductions in carbon emissions (Vanclay *et al.*, 2011). However, the current systems of carbon labelling do not communicate a meaningful message to the consumer, if the label simply presents the emissions value on the product package (Upham, Dendler and Bleda, 2011). According to the responses from a survey of carbon labelling, it is clear that the public find it quite difficult to imagine a given quantity of CO2 emission and its potential environmental impact

(Gadema and Oglethorpe, 2011). Thus, the carbon label still needs improvement in the clarity of current carbon labelling schemes, so as to encourage consumers to select low carbon products, as well as increase the potential for public carbon footprint reduction.

Meanwhile, Society should also focus on achieving waste materials sustainability, by transforming from “Cradle to Grave” into “Cradle to Cradle”, to create a closed-loop system for waste free, thus to improve the product quality being environmentally friendly (Lovins, 2008). The concept of “Cradle to Cradle” is firstly put forward by Walter R. Stahel in the 1970’s, and developed sub-sequentially by Dr. William McDonough and Dr. Michael Brauggart. Their collaborative publication “Cradle to Cradle: Remaking the Way We Make Things” in 2002, which firstly demonstrates how to achieve the model. This approach divides all materials into to two categories: ‘technical’ or ‘biological’ nutrients (see Fig.1.2). Technical nutrients are those materials which are non-toxic, non-harmful, and consequently have less environmental risk or negative impact on the natural environment. These kinds of materials can be reused directly in continuous cycles without losing their integrity or quality, or recycled parts of their quality and functionality, for example the cola bottle. Biological nutrients are organic materials, which can be decomposed into the soil as fertilization to provide food for microorganisms without affecting the natural environment. Both nutrients are in order to prevent waste materials, reduce consumption of raw materials, energy consumption, and environmental risk (McDonough and Brauggart, 2002). In this context, environmental consideration has played an important role in materials selection, which is an increasing requirement in product design to provide better, safer and sustainable products for public consumption.

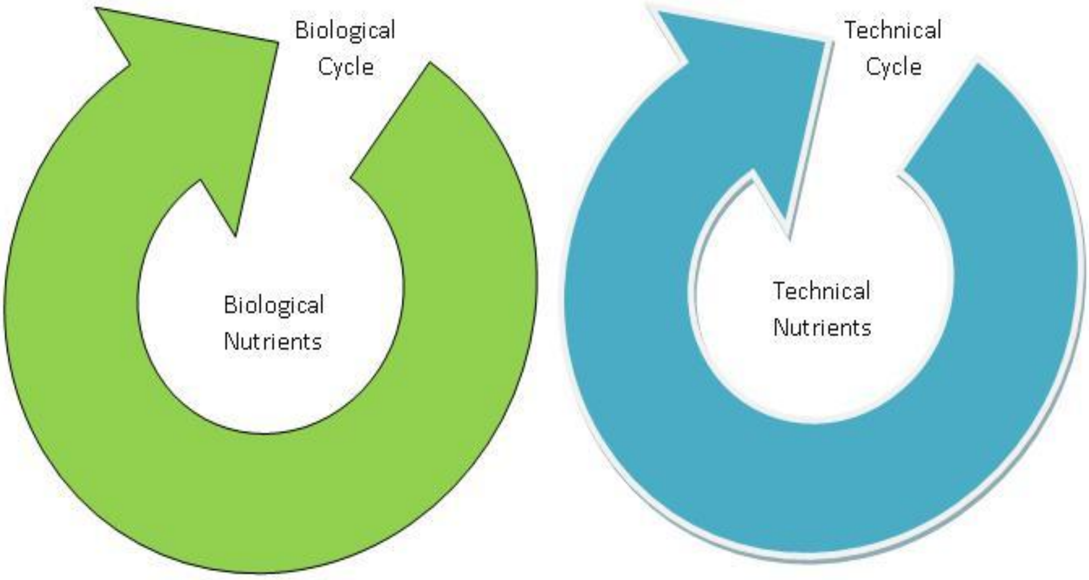

Fig.1.2. A “Cradle to Cradle” model (adopted from McDonough and Brauggart, 2002)

In summary, as society is facing major environmental challenges, is it possible to achieve sustainability by using less natural resources, optimizing recycling and reusing waste materials (DEFRA, 2008)? This PhD project focuses mainly on the design of an environmental management system for hazardous waste materials in order to reduce environmental risk and the associated impact, as well as to battle against ‘climate change’.

1.3 Aims and objectives

The main aim of this PhD study is to develop a "decision support system" for application by engineering designers to minimize environmental risk and thus to minimize the associated carbon footprint, through the application of 'game theory', 'grey theory' and various computational approach, to help the designer identify novel solutions, mitigation strategies.

Specifically, the objectives for the PhD study are presented below:

Identify an appropriate indicator to better understand the environmental impacts of products, which is easily communicated and consistent with the concept of sustainability (TBL).

Using Systems Theory, evaluate the 'problem situation' and develop a conceptual model for hazardous waste materials to understand the principal drivers, actors, *etc.* and influences upon the ultimate environmental impact.

Using game theory, simulate the possible actions of government and manufacturers in the context of a 'game', in order to achieve more environmentally friendly products.

Using game theory, with a novel underlying mathematical model, identify the most appropriate strategy in the context of “green supply chain management”, for manufacturers of commercial products optimising the three dimensions of sustainability (TBL).

Using grey theory, develop a design tool, to facilitate materials selection, adapt product design to promote cleaner production, provide sustainable products for public consumption and achieve long term commercial success.

By combination of the approaches outlined above, provide new understanding and novel solutions with regard to societal change, by the provision of a new design for a risk management decision support system for hazardous waste materials which could suggest mitigation strategies.

1.4 Research approach

This study involves various computational approaches to limit environmental burden and to reduce the risk and the carbon footprint, and can be divided into following stages (See Fig.1.3). The technical path starts from the statement of the set research aim, and the first process is a literature review, which are covered by Chapter 2, in order to understand the status of previous studies and set this research in context.

Based upon the literature review, the problem situations can be described more clearly and more specifically. The functional framework of the proposed system is designed in terms of the 'analysis of problems'. Sequentially, the proposed decision support system for hazardous materials is developed by means of modular design, according to the system framework (See Fig.1.4).

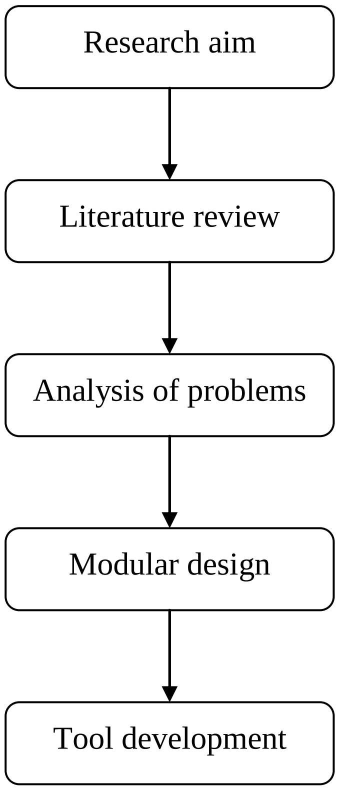

Fig.1.3. Process of the research

The proposed decision support system is mainly divided into three modules: application of tolerability of risk, materials selection and carbon label improvement. The latter two modules can be connected closely by the application of tolerability of risk, through which the carbon emissions intensity ratio is introduced to set up the appropriate carbon criteria, as well as cleaner production can be promoted by reducing environmental risk and carbon footprint. With such environmental and economic factors being considered by materials selection, products can be improved further to be more 'environmentally friendly', thus minimizing the risk as well as reducing the environmental impact. Moreover, followed by the introduction of a new carbon labelling scheme for products, consumer's preferences on products purchasing behaviour may be affected. In this case, organisations have to reconsider their strategies for production and Government should be also involved in this situation to regulate the environmental unfriendly actions by manufacturers. Due to their different behaviours, various interests and conflicts may be generated. Thus, the application of the game theory integrated with dynamic optimization technique can provide insight to solve these interactions. There are at least three important boundaries according to the game situation, Government | Manufacturer, Manufacturer | Manufacturer, and Manufacturer | Consumer. This study mainly focuses on the first two dynamic boundaries.

At the last stage, the decision support tool corresponding to the functional modules will be developed by means of computer programming. For example, the integrated evaluation approach is embodied into a computational tool based on a spreadsheet application (Microsoft Excel 2007) to aid decision making.

1.5 Thesis layout

The introduction section starts to provide a brief background of this research topic and then discusses the problem situation, whilst the research aim, objectives and approach are put forward.

Chapter 2 presents a review of previous studies which are related to the research, *e.g.* hazardous materials or waste, environmental risk, carbon footprint, game theory applications and decision support systems. The current research status will be summarized to provide insight on this research and set it in context.

Chapter 3 identifies a new indicator ‘Carbon Emissions Intensity Ratio (CEIR)’ by normalizing carbon emissions data on a common scale, to improve the current carbon labelling scheme. A diagram with colour-coding is developed to represent the degrees of carbon emissions intensity ratio, to encourage consumers to select low carbon products, and thus increase the potential for reduction in carbon emissions.

Game theory is a novel approach in this study, which is proposed to aid decision-making on strategy selection for promoting ‘cleaner production’, reducing the environmental risk and carbon emissions caused by ‘hazardous’ materials in the whole supply chain. Chapter 4 provides the basis of game theory, which will be used for further game theoretical analysis and simulation in Chapter 5 and 6. The “Prisoners’ dilemma", which is the prototype for many game situations, is introduced as an example to illustrate how game theory is used to predict the strategic action.

Chapter 5 discusses the possible game scenarios in the context of 'cleaner production', generated by a "Two-person Non-cooperative" game model, which examines various strategic options selected by government and manufacturers, to promote cleaner production whilst maximizing the economic and environmental profits. In addition, the software package 'Gambit' is selected for the analysis to demonstrate the game problem situation more visually.

Chapter 6 develops the game scenario of 'cleaner production' further, by applying it to supply chain networks, and analyzes the strategies selected by manufacturers of the 'hazardous' materials in the context of 'green supply chain management', to reduce the environmental risk and the associated carbon emissions.

In addition to the optimal strategy selected by manufacturers in the supply chain for the risk and carbon footprint reduction, Chapter 7 employs the dynamic optimisation technique to minimize the total economic cost, followed by maximizing the reduction extent of inherent risk and the associated carbon footprint.

In order to provide better, sustainable products for public consumption, as well as promote cleaner production by reducing the 'hazardous' materials consumption and carbon footprint that products contain, environmental consideration should become more important in product design and especially in the field of materials selection. In this context, Chapter 8 introduces a convenient approach to materials selection for application by engineers to aid decision-making taking environmental evaluation into account.

Chapter 9 gives conclusions derived from each preceding chapter, and discusses the research limitations, laying a foundation for further work. Future studies are proposed based upon the concluding remarks and limitations.

Finally, a user manual is provided in the Appendix A, which demonstrates how to use the functional modules of the developed decision support tool. Moreover, all the related conference and journal publications are listed in the Appendix B and C.

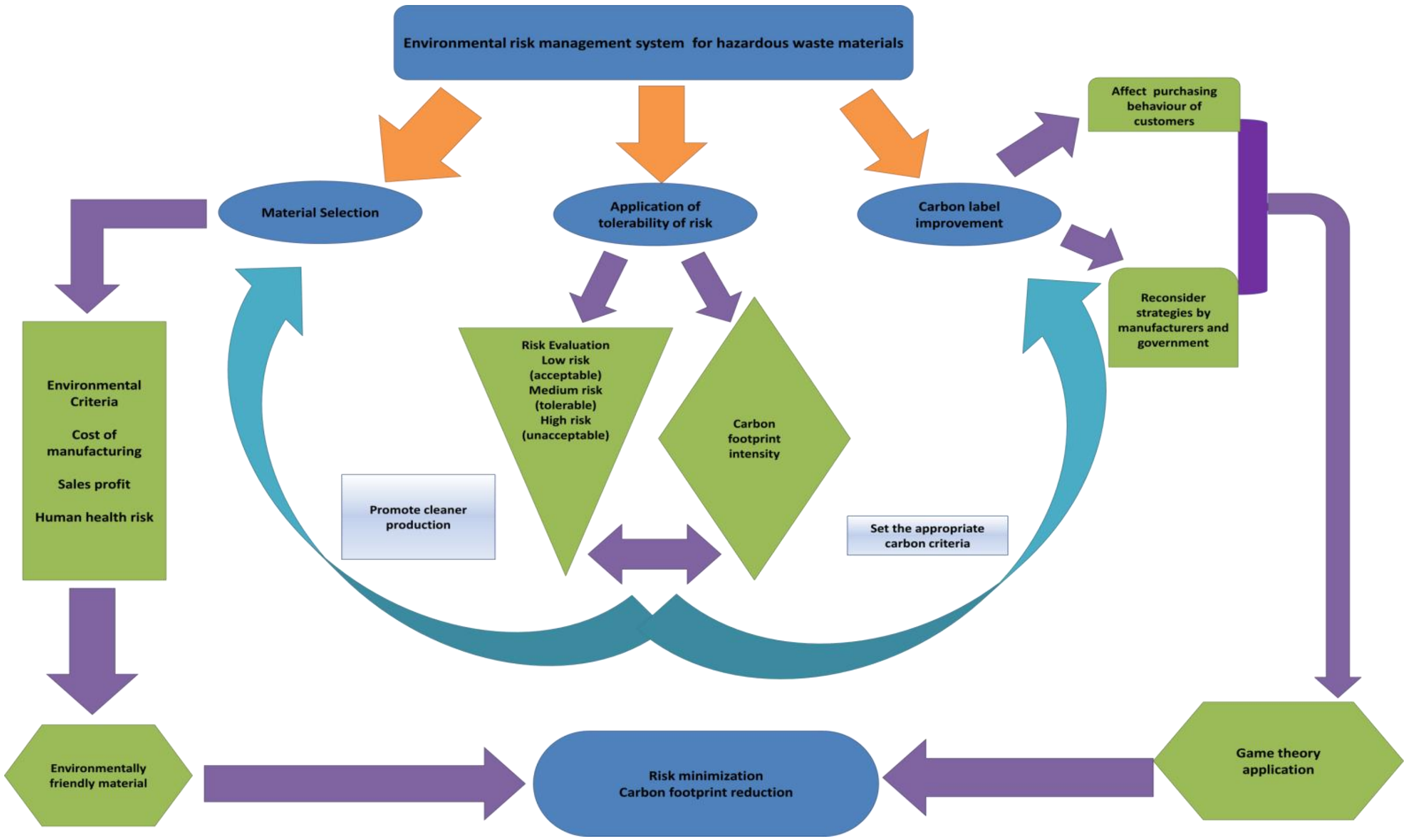

Fig.1.4. Framework of the proposed decision support system

Chapter 2: Literature Review

2.1 Hazardous materials and hazardous waste

2.1.1 Definition

According to UK regulations, hazardous materials or substances are defined as "*any substance or group of substances which are toxic, persistent, and liable to bio-accumulate*" (DEFRA, 2009). Thus these materials are a potential threat to the environment. Moreover, hazardous substances have the potential to pollute the environment, and accumulate in animals or human well-beings in the long term (Environment Agency, 2009).

In the United States, the definition of hazardous materials is differentiated in each Department. For instance, the US Department of Transportation (DOT) defines that hazardous material as " *a substance or material capable of posing an unreasonable risk to public safety or the environment when being transported or moved in commerce, and designated as hazardous under the Federal hazardous materials transportation law* "(49 CFR 100-180).

American Occupational Safety and Health Administration (OSHA) states hazardous materials to be the hazardous chemical specifically, which identified any hazardous substance to be a "*health hazard*" or "*physical hazard*", including "*chemicals which are carcinogens, toxic agents, irritants, corrosives, sensitizers; agents which act on the hematopoietic system; agents which damage the lungs, skin, eyes, or mucous membranes; chemicals which are combustible, explosive, flammable, oxidizers, pyrophorics, unstable-reactive or water-reactive*"; and "*chemicals which in the course* *of normal handling, use, or storage may produce or release dusts, gases, fumes, vapours, mists or smoke which may have any of the previously mentioned characteristics*” (29 CFR 1910.1200).

It is evident that there are different definitions for hazardous materials as above, in terms of the regulations from different countries and organisations. However, hazardous materials can be generally deemed as “*anything which, because of its quantity, concentration, or physical, chemical, or infectious characteristics may cause, or significantly contribute to, an increase in mortality; or cause an increase in serious irreversible, or incapacitating reversible, illness: or pose a substantial present or potential hazard to human health and the environment when improperly treated, stored, transported, or disposed of, or otherwise managed*”(Lee, 2005; De Lisi, 2006). Moreover, this definition will be used throughout this study.

Hazardous waste is distinguished from hazardous materials in this study. With regard to the definition of hazardous waste, it is defined in the United Kingdom as to be certain kinds of waste which possess hazardous properties that may cause environmental risk or be harmful to human health (DEFRA, 2005). In the United States, Resource Conservation and Recovery Act (RCRA) describes “*hazardous waste” to be “a solid waste, or combination of solid wastes, due to its quantity, concentration, physical, chemical or infectious characteristics, which may cause, or significantly contribute to an increase in mortality (death) or an increase in serious irreversible, or incapacitating reversible illness; or pose a substantial (present or potential) hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed* ” (Liu and Lipták, 1997; Garrett, 2004). In addition, United Nations Environment Programme has elaborated the definition of hazardous waste as “*wastes* *which, by reason of their chemical activity or toxic, explosive, corrosive, or other characteristics, cause danger or likely will cause danger to health or the environment, whether alone or when coming into contact with other waste*" (Lagrega et al., 2001).

Nevertheless, it is important to note that there is no exact definition for 'hazardous waste materials' since any waste with properties of ignitability, corrosivity, reactivity, toxicity *etc*., can be mixed during the process of production, deposit, transportation, treatment, as well as ultimate disposal, can cause impairment of the environment (Tchobanoglous, 2000). According to the Hazardous Waste (England and Wales) Regulations 2005, there are fifteen typical hazardous waste materials resulted from the daily consuming activities which are listed below (DEFRA, 2005b): Acides; Alkaline solutions; Batteries; Oil fly ash; Industrial solvents; Oily sludges; Pesticides; Pharmaceutical compounds; Photographic chemicals; Waste oils; Wood preservatives; TVs; Computer monitors; Paint; Fluorescent tubes. Clearly, this is a rather simplistic viewpoint.

2.1.2 Comparative analysis between hazardous materials and waste

Primarily, the comparative analysis between hazardous materials and hazardous waste starts from their similarities. The characteristics of hazardous materials or hazardous waste are more or less the same. Moreover, any hazardous materials or hazardous waste may have at least one of these four characteristics (Blackman, 2001; Enger and Smith, 2004). Due to these harmful properties, it is significant to control the inherent risk at the initial stage (design phase), as the potential harm can be immediate (short term) or delayed (long term).

1. Ignitability
2. Corrosivity
3. Reactivity
4. Toxicity

The apparent difference between hazardous materials and hazardous waste has legal and regulatory implications (Enger and Smith, 2004). At its simplest, waste is considered as any material that has no value. If a material has any value, be it treated or not, it can be still considered as a 'commodity'. Discarded products, *e.g.* computers, can be considered to be a commodity, due to the value of metals contained. Thus, hazardous waste management is involved of many uncertainties.

2.1.3 Hazardous waste management

Relevant laws and regulations are designed to ensure the implementation of hazardous waste management at an early stage. The European Commission has issued a Directive on the correct management and regulation of hazardous waste (HWD, Council Directive 91/689/EC), and such waste is defined on the basis of a list, the European Waste Catalogue (EWC 1994, Commission Decision 94/3/EC), drawn up under that Directive. Council Decision 94/904/EC then identified which of the wastes on EWC 1994 are deemed to be hazardous, based on the properties set out in the HWD. There are 14 hazardous properties set out by the HWD with the details reflected in Table 2.1 (Environment Agency, 2009; DEFRA, 2009), but it should be noted that this is very a partial view in comparison to the earlier definitions of hazardous materials.

Table 2.1 Typical hazardous properties
(Adopted from: Hazardous Waste Directive Annex III)

H1	"Explosive": substances and preparations which may explode under the effect of flame or which are more sensitive to shocks or friction than dinitrobenzene.
H2	"Oxidising": substances and preparations which exhibit highly exothermic reactions when in contact with other substances, particularly flammable substances.
H3A	"Highly Flammable": liquid substances and preparations having a flashpoint of below 21 ℃ (including extremely flammable liquids), or substances and preparations which may become hot and finally catch fire in contact with air at ambient temperature without any application of energy, or solid substances and preparations which may readily catch fire after brief contact with a source of ignition and which continue to burn or to be consumed after removal of the source of ignition, or gaseous substances and preparations which are flammable in air at normal pressure, or substances and preparations which, in contact with water or damp air, evolve highly flammable gases in dangerous quantities.
H3B	"Flammable": liquid substances and preparations having a flashpoint equal to or greater than 21 ℃ and less than or equal to 55 ℃.
H4	"Irritant": non-corrosive substances and preparations which, through immediate, prolonged or repeated contact with the skin or mucous membrane, can cause inflammation.
H5	"Harmful": substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may involve limited health risks.
H6	"Toxic": substances and preparations (including very toxic substances and preparations) which, if they are inhaled or ingested or if they penetrate the skin, may involve serious, acute or chronic health risks and even death.
H7	"Carcinogenic": substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce cancer or increase its incidence.
H8	"Corrosive": substances and preparations which may destroy living

	tissue on contact.
H9	"Infectious": substances containing viable micro-organisms or their toxins which are known or reliably believed to cause disease in man or other living organisms.
H10	"Toxic for reproduction": substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may produce or increase the incidence of non-heritable adverse effects in the progeny and/or of male or female reproductive functions or capacity.
H11	"Mutagenic": substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce hereditary genetic defects or increase their incidence.
H12	Substances and preparations which release toxic or very toxic gases in contact with water, air or an acid.
H13	Substances and preparations capable by any means, after disposal, of yielding another substance, e.g. landfill leachate, which possesses any of the characteristics listed above.
H14	"Ecotoxic": substances and preparations which present or may present immediate or delayed risks for one or more sectors of the environment.

With several years of consultation and development among the EU countries, the EWC 1994 has been updated, resulting in a revised European Waste Catalogue (EWC 2002, Commission Decision 2000/532/EC). There are two highlighted aspects of the revised catalogue in contrast with the EWC 1994: a catalogue of all wastes, classified in terms of generic industry, process or waste type; a distinction between non-hazardous and hazardous by identifying hazardous waste entries with an asterisk (Environment Agency, 2009). Fig.2.1 presents a flowchart about how to determine whether a waste is hazardous or non-hazardous.

Similarly, Waste Framework Directive 2008/98/EC has integrated HWD 91/689/EEC and Directive 94/31/EC, to simplify European Union legislation on waste management.

The obligations of hazardous waste management such as keeping, monitoring and controlling, has been provided from the "Cradle to Grave", *i.e.*, from the waste producer to the final disposal or recovery. Moreover, more attention has been paid in the Directive to preventing risks for the environment and human health, when different categories of hazardous wastes are mixed together, or with non hazardous wastes. In addition, the permit exemptions that allow the related infrastructure or installations dealing with hazardous wastes are more restrictive than dealing with other wastes (European Commissions Environment, 2010).

On 16 July 2005, the Hazardous Waste Directive was implemented in the UK by the Hazardous Waste (England and Wales) Regulations 2005 and the List of Waste (England) Regulations. The new regulations have come into force replacing the Special Waste Regulations, which was transposed from the European Hazardous Waste Directive (91/689/EEC) (DEFRA, 2007). The Hazardous Waste (England and Wales) Regulations 2005 (S.I. 2005 No 894) is comprised of thirteen chapters, from which general introduction of hazardous waste, distinguishing between hazardous and non-hazardous waste, mixing hazardous waste, movement of hazardous waste, hazardous waste premises and records *etc.*, has been discussed respectively (HMSO, 2005). The regulations are designed in order to simplify the documentation associated with the collection and disposal of hazardous waste, as well as implement in accordance with EU legislation. Moreover, the ultimate objective is to improve hazardous waste management, protect human health and reduce environmental risk as a whole (PHS Group, 2005). Following a long term public consultation, there are some amendments to the Hazardous Waste (England and Wales) Regulations 2005, and the latest regulations have been validated since 6 April 2009, as Hazardous Waste (England and Wales) Regulations 2009 (S.I. 2009 No 507) which is more detailed and comprehensive to clarify certain provisions of the 2005 Regulations. Another prominent change reflects the exemption from hazardous waste producer registration, on which the qualifying limitation of hazardous waste output per year is adjusted to 500 Kg instead of 200 Kg (DEFRA, 2010; Environment Agency, 2010).

On the basis of Waste Framework Directive 2008/98/EC and Hazardous Waste (England and Wales) Regulations 2009 (S.I. 2009 No 507), the Strategy for Hazardous Waste Management in England has been formulated and implemented since 18 March 2010. This strategy determined the revised waste hierarchy with respect to hazardous waste, as well as intended to facilitate the provision of infrastructure for the hazardous waste management. The ultimate aim of the strategy is to manage hazardous waste in more economically and environmentally ways, through the combined effort of members of the public, local authorities, trade associations, businesses, non-governmental organisations and consumer groups *etc* (DEFRA, 2010). Specifically, the strategy mainly consists of four parts: a set of six principles for the environmentally sound management of hazardous waste; a series of outline decision trees to help waste producers and managers determine the best management solution for the hazardous waste, as well as help move hazardous waste management up the waste hierarchy via cost-benefit analysis in infrastructure; a timeline of action on issues related to the introduction and implementation of the strategy; a list of relevant guidance to the treatment of hazardous waste and proposed further guidance by DEFRA or Environment Agency (DEFRA, 2010).

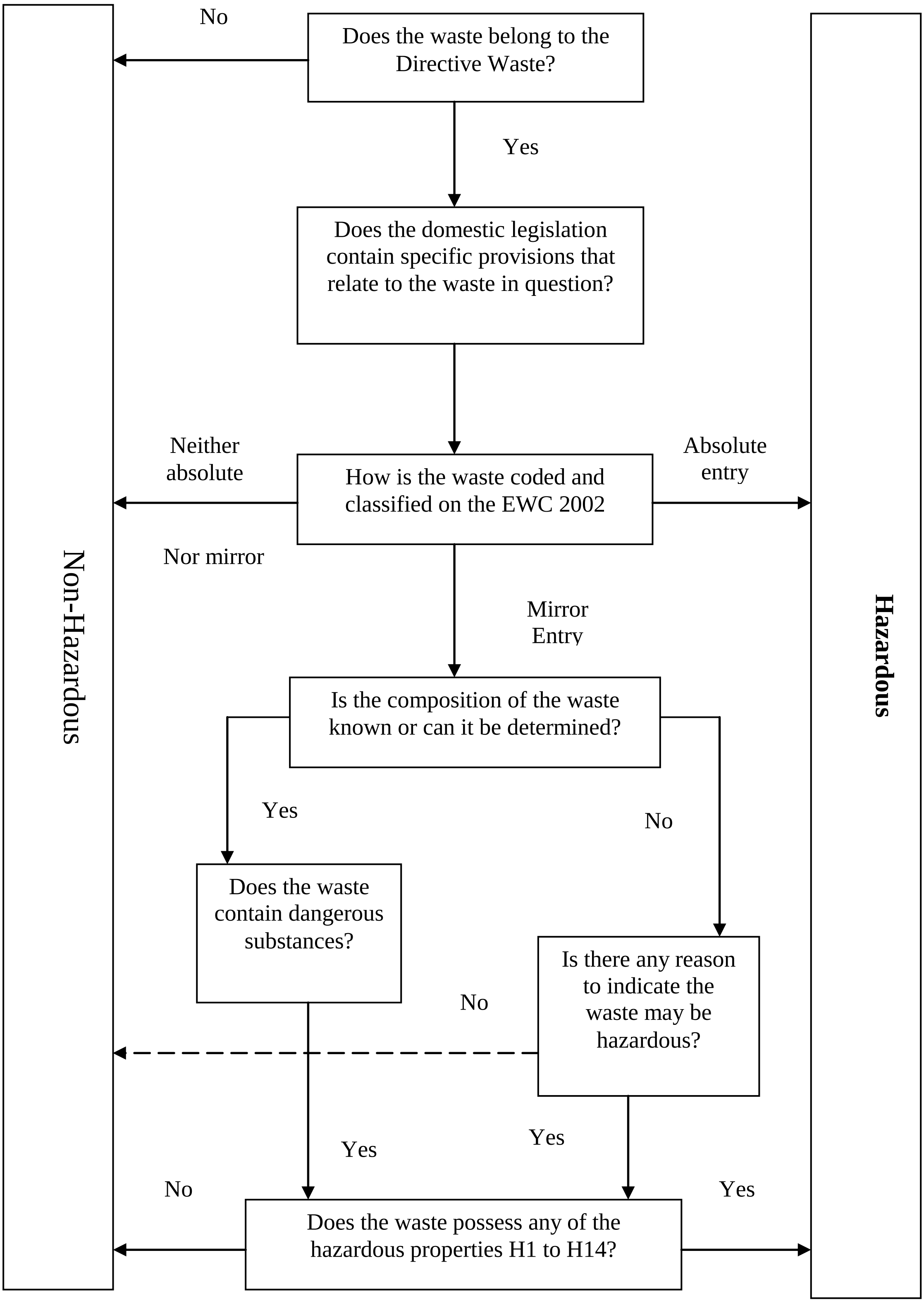

Fig.2.1. Flowchart of distinction between hazardous and non-hazardous (adopted from: Environment Agency, 2005)

In addition to above regulations set for hazardous waste management, whilst taking public health and safety, the overall environmental impact into account, hazardous waste streams should be departed from the waste hierarchy, where it is justified by life cycle assessment on the overall environmental impacts from the generation to the final disposal (DEFRA, 2007). Fig.2.2 shows the waste hierarchy for hazardous waste management, incorporated with waste prevention at the top and disposal at the bottom. From the standpoint of "hierarchy of waste management", the most preferable state encompassing sustainable development is to prevent or eliminate the waste. Waste prevention includes relevant measures or techniques that reduce the adverse impact of hazardous waste on the environment and human health, as well as reduce not only the quantity of hazardous waste produced, but also the content of harmful substances in raw materials and products before converting to hazardous waste (National Research Council, 1995; Allen and Rosselot; 2004; DEFRA, 2010).

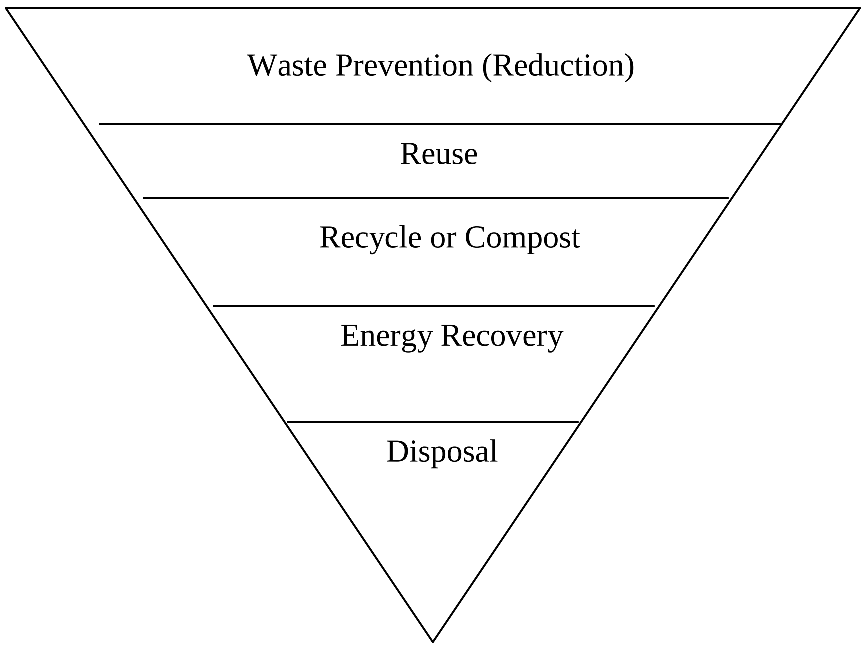

Fig.2.2. Hierarchy of waste management (adapted from: DEFRA, 2007)

The hierarchy has also incorporated with the “3R concept”, which provides a framework for hazardous waste management in terms of the possible environmental consequence. “3R concept” focuses on waste *reduction, reuse and recycling*, which aims at reducing the waste disposal in the landfill, consequently the landfill gas and leachate emitted to the environment, thus reducing the total environmental impact and saving the energy and natural resources (Zhu, Sarkis and Lai, 2008). Fig.2.3 shows that the waste hierarchy has been divided into three stages in real terms: resource management; recovery by means of various techniques, *i.e.* recycling from different waste materials, heat recovery from the pyrolysis or incineration; final disposal, respectively. Waste prevention as mentioned above, should be involved within the resource management not only to reduce the waste amounts but also the potential toxicity. However, this is not wholly practical in real terms. Options of reusing or recycling, *e.g.* waste exchange, should be employed and promoted during the waste management. By analogy, when such opportunities as reusing and recycling have been all exhausted, the waste treatments like incineration or other thermal methods need to be developed before disposal in landfill (Soesilo and Wilson, 1995; DEFRA, 2007 and 2010). Furthermore, each stage in the hierarchy may generate residues, which need to be carefully managed.

Although the waste hierarchy provides a general principle for waste management (Williams, 2005), there are some limitations which impede its practical implementation. First of all, the hierarchy itself does not consider the overall impacts within a given waste management system, as it focuses more on waste materials elimination but gives less attention to the economic and energy aspects. For instance, some underdeveloped or developing countries would prefer landfill as the primary disposal approach instead of other thermal treatment process with respect to the economic consideration.

Secondly, how to treat the residues from the reusing, recycling or the energy recovery processes (*e.g.* the fly ash generated from the incinerators) can be another issue of the waste hierarchy. In addition, for those hazardous waste materials which present a risk to the public health and the environment throughout their life cycle, the hierarchy may involve difficulties and uncertainties on how to select the appropriate options for the waste treatment and disposal (White, Franke and Hindle, 1995; Williams, 2005). Thus, it is suggested taking a more holistic way to manage waste contained hazardous substances in this study, *e.g.* using the product lifecycle management to mitigate the environmental risk and impact.

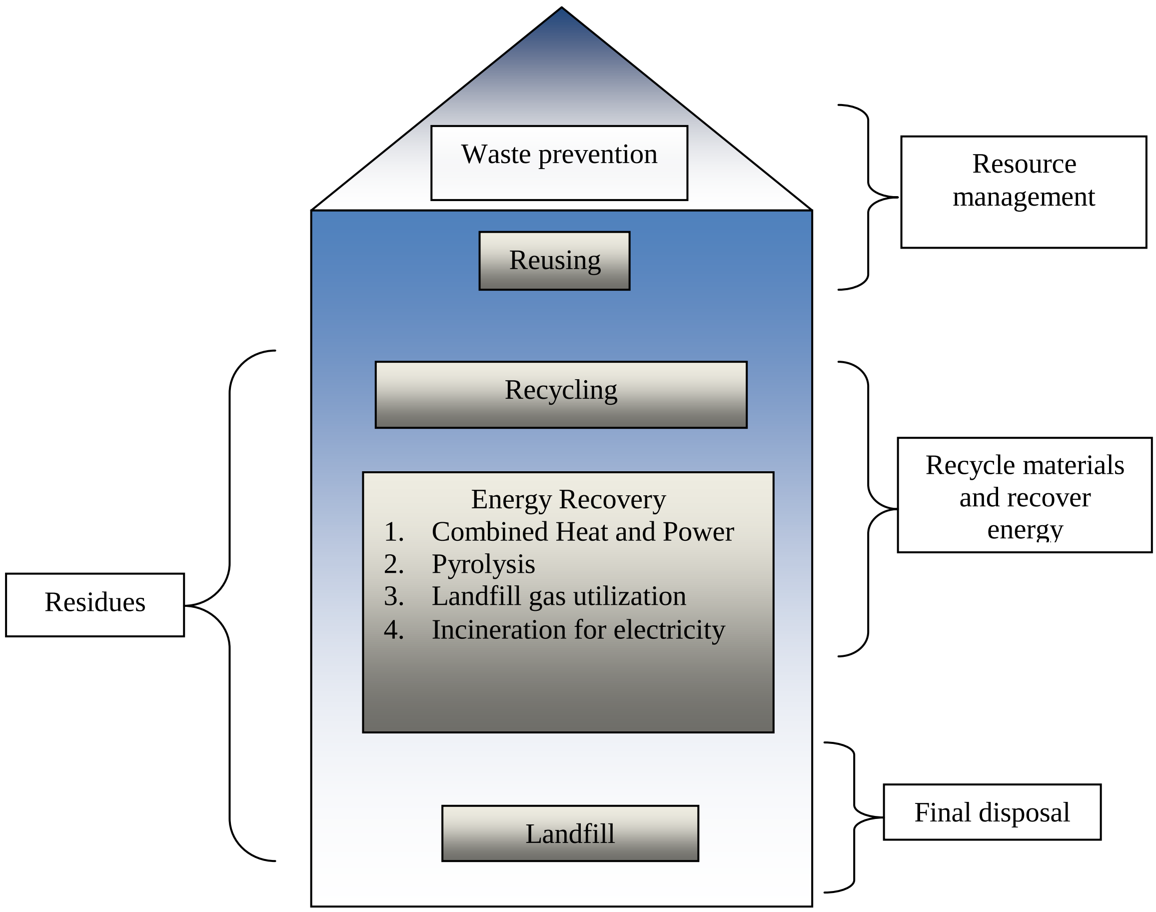

Fig.2.3. The detailed framework of the waste hierarchy (adopted from Williams, 2005)

2.1.4 Product life cycle management

Product lifecycle management (PLM) is an effective tool which provides an approach to control the product process in a specific business or manufacturing area, from product design, development to marketing, final disposal in the post-consuming stage (Saaksvuori and Immonen, 2005). With natural resources being exploited at an increasing rate, as well as the threat of "climate change", the product life cycle management has also to take the environmental impact into account, for instance to use lifecycle assessment to investigate such indicators as environmental risk, carbon emissions *etc.* This aims at reducing the total environmental impact throughout the product lifecycle, "from sunrise to sunset" (Stark, 2005). Therefore, product lifecycle management can be combined with the waste management and risk management to handle hazardous materials or hazardous waste materials effectively, especially to reduce environmental risk and negative impact during various stages of the product lifecycle, *i.e.* design, production, transportation, use and decommissioning. However, the literature is weak in this area and demonstrates the need for this study. For instance, many manufacturers still primarily focus on the profit as the bottom line for business (Henriques, 2004), while not taking the full lifecycle of products into account, and even do not regard waste management as a key business area. In addition, studies have shown that smaller organizations have paid less attention to "waste prevention" or "cleaner production" (European Environment Agency, 2003). From the perspective of the 'Hierarchy of Waste' (See Section 2.1.3), the preferable strategy for encompassing sustainable development is to prevent or eliminate waste (DEFRA, 2007). Waste prevention or 'cleaner production', which is defined as "*the continuous application of an integrated, preventive strategy to processes, products and services to increase efficiency and reduce risks to humans and the environment*" (UNEP, 2006), and has been demonstrated as the best model for pollution prevention within the product life cycle management, the best way to promote economic benefits and the most effective way to implement sustainable development (China NDRC, 2008). The following sections review how to select the appropriate materials to promote cleaner production at first, and then review two indicators which significantly affect the sustainability of a product's life cycle, environmental risk and carbon footprint respectively.

2.1.5 Environment oriented materials selection

Materials selection can be done in different ways, but the principles are quite similar. Generally, selection of materials for products is principally driven by function and structural demands, requiring considerations of mechanical, physical and chemical properties (Ashby, 2005). In addition, cost and availability are equally important considerations. With the threat of "climate change", the term "environmental conscious design" has gradually emerged in manufacturing, in particular focusing on "design for environment" in the context of sustainable development (Kalpakjian and Schmid, 2006). The main objective of this approach is to mitigate the adverse impact on the environment and human health by decreasing the amount or toxicity of raw materials used in a product; redesigning products in order to increase their lifecycle, reusability and reparability; reforming the quality of products; reducing the amount and toxicity of waste generated, *etc* (Tchobanoglous, 2002; Allen and Rosselot; 2004; Williams, 2005). Therefore, environmental consideration is an increasing requirement in materials selection. Holloway (1998) has extended the Ashby flow diagram of materials selection by taking environmental factors into account for mechanical design, in which air and water pollution are calculated and plotted on the Ashby's energy content chart to help engineers or designers better understand the optimal environmental design criteria. Ermolaeva, Castro and Kandachar (2004) have used life cycle assessment (LCA) to aid materials selection in an automotive structure, based upon structural optimization. Three important indicators have been considered, as ‘Disability-Adjusted Life Years (DALY)’, ‘Potentially Disappeared Fraction (PDF)’, ‘Mega Joule’ (MJ), which are used for the environmental impact assessment, corresponding to areas of ‘Human Health’, ‘Ecosystem Quality’ and ‘Resources’ accordingly. According to the LCA, it is suggested that low-density phenolic foam can be used as a core material for an automotive structure. In a similar study, Bovea and Vidal (2004) have applied LCA methodology to selecting materials with low environmental impact during the process of wood-based furniture design. Further, Giudice, Rosa and Risitano (2005) have applied a product life-cycle design approach to the selection of materials, not only to meet the product requirements of functionalities and performances, but also to minimize the environmental impact from ‘Cradle to Grave’. The brake disc is cited as a case example, and shows how this approach can be integrated with conventional design methods.

In addition, products are increasingly being developed that are less damaging to the environment, gradually moving towards the concept of ‘sustainability’. Thus, Ljungberg (2007) has suggested that more renewable and easy recyclable materials be selected for sustainable product design, aimed at environmental impact reduction, usually referred to as ‘design for environment’. Further, Zhou, Yin and Hu (2009) have built a multi-objective optimisation model of materials selection for sustainable products, in which life cycle assessment is integrated with artificial neural networks.

While these previous studies are very useful in informing our approach, most of them have used the life cycle assessment (LCA) approach to materials selection in terms of environmental consideration, which is still a complex process involving a large amount of available data to determine the specific scenarios, thus limiting its wider application (Yang, 2007; Zhou, Yin and Hu, 2009). There is thus a need for an approach that is simple to use. In addition, most existing studies present methods for selecting between widely different materials (Bovea and Vidal, 2004; Ermolaeva, Castro and Kandachar, 2004; Giudice, Rosa and Risitano, 2005). However, while choosing between materials with substantially different properties is a relatively straightforward task, selection between similar materials, or different varieties of the same material, would require highly precise data.

2.2 Environmental risk

2.2.1 Definition

Risk is defined as "*a combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of the occurrence*" (DETR, 1995). This is a two dimensional definition which describes the risk as integrating the undesirable outcome with the probability of that outcome. Based upon the two dimensional definition of risk, Kaplan and Garrick (1981) have considered risk as a triple dimension, representing $R_i = \{S_i, P_i, C_i\}$. In terms of this equation, S_i is indicated as scenario i, P_i the probability of scenario i, and C_i the consequence of scenario i. In this definition, the scenario describes the conditions which are set for some event to happen (*e.g.* environmental contamination such as explosion, flood *etc*); the probability represents the likelihood; whilst the consequence indicates the impact of a corresponding scenario. Compared with the two dimensional definition of risk, the triple one is much more specific, since different consequences may result from the predetermined scenarios. Thus, it is much more practical and applicable for further risk assessment and analysis.

In brief, environmental risk can be defined as "*a measure of potential threats to the environment and the total loss of value that human health resulting from the presence of environmental hazards, as well as combines the probability which events will cause degradation of the environment and the severity of the degradation*" (Cothern, 1996; Pritchard, 2000). Moreover, the environmental hazards within the definition can be seen as a source of risk (Wilson, 1991). From the viewpoint of system thinking, environmental risk can be determined by the following key factors, and each factor interacts sequentially from the source to the final consequences (see Fig.2.4).

1. The source of the risk (*e.g.* hazardous materials or hazardous waste);

2. The potentially affected objects or the targets (*e.g.* various media such as human being, plants, animals, air, water, soil *etc*);

3. the potential environmental impact (*e.g.* the water, waste pollution, greenhouse gas emission);

4. the possible consequences and impact (*e.g.* the impacted extent and area including fatalities, injuries, property damage *etc*).

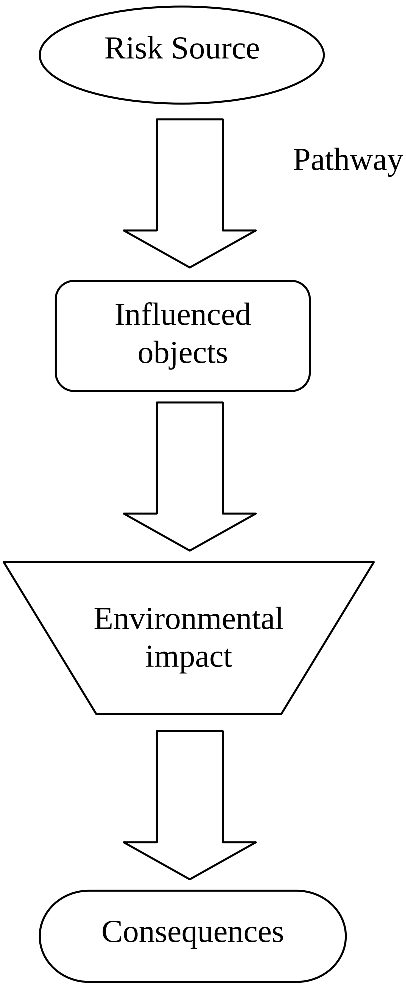

Fig.2.4. Definition of environmental risk in a systematic view

In this study, the risk to the environment resulting from the complete supply chain involving ‘hazardous’ materials, and the attendant health implications, needs to be carefully assessed in the context of the product life-cycle. Fig.2.5 shows that the public may be at environmental risk throughout the product’s full lifecycle of hazardous materials, from extraction to final disposal. Certainly, this is scarcely considered in the literature. It follows that there is a need to consider the risk to society associated with everyday consumer products.

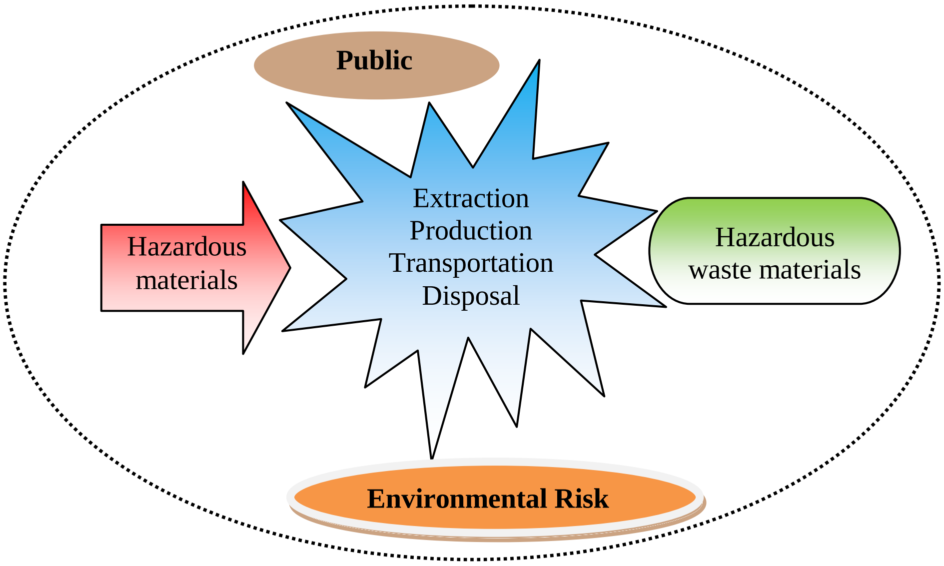

Fig.2.5. Environmental risk throughout product's full lifecycle

2.2.2 Environmental risk management

Environmental risk management can be interpreted as an integrated decision making process, which is a multi-phase analysis comprised of risk identification, environmental risk assessment, further regulatory or non-regulatory alternatives, implementation of management strategy and monitoring (Gough, 1996; Morris and Therivel, 2009). Fig.2.6 presents a basic framework for an integrated approach to environmental risk assessment and management, where the level of effort put into assessing each risk is related to its priority (to compare with other risks *e.g.* economic or financial risk) and its complexity (in order to understand the possible impacts or consequences) (DETR, 1995).

In the field of hazardous waste management, environmental risk assessment is an essential tool to provide significant information for decision makers, such as the frequency of environmental hazards, the possible damaging consequences in a predetermined scenario and how best to manage various kinds of risk. Moreover, environmental risk assessment demands better understanding of a risk source, *e.g.* the hazardous waste materials, and the characteristics of an environmental receptor that may be at risk from this hazard and the pathway through which the receptor maybe affected, which can be seen from Fig.2.5. Such management measures, based upon the risk assessment, could reduce the inherent risk to public health caused by hazardous materials/waste from production to final disposal. This is also available to select appropriate facilities for hazardous waste treatment or disposal, remediate the contaminated sites, minimize waste generation, and develop new products *etc* (Lagrega, Buckingham and Evans, 2001).

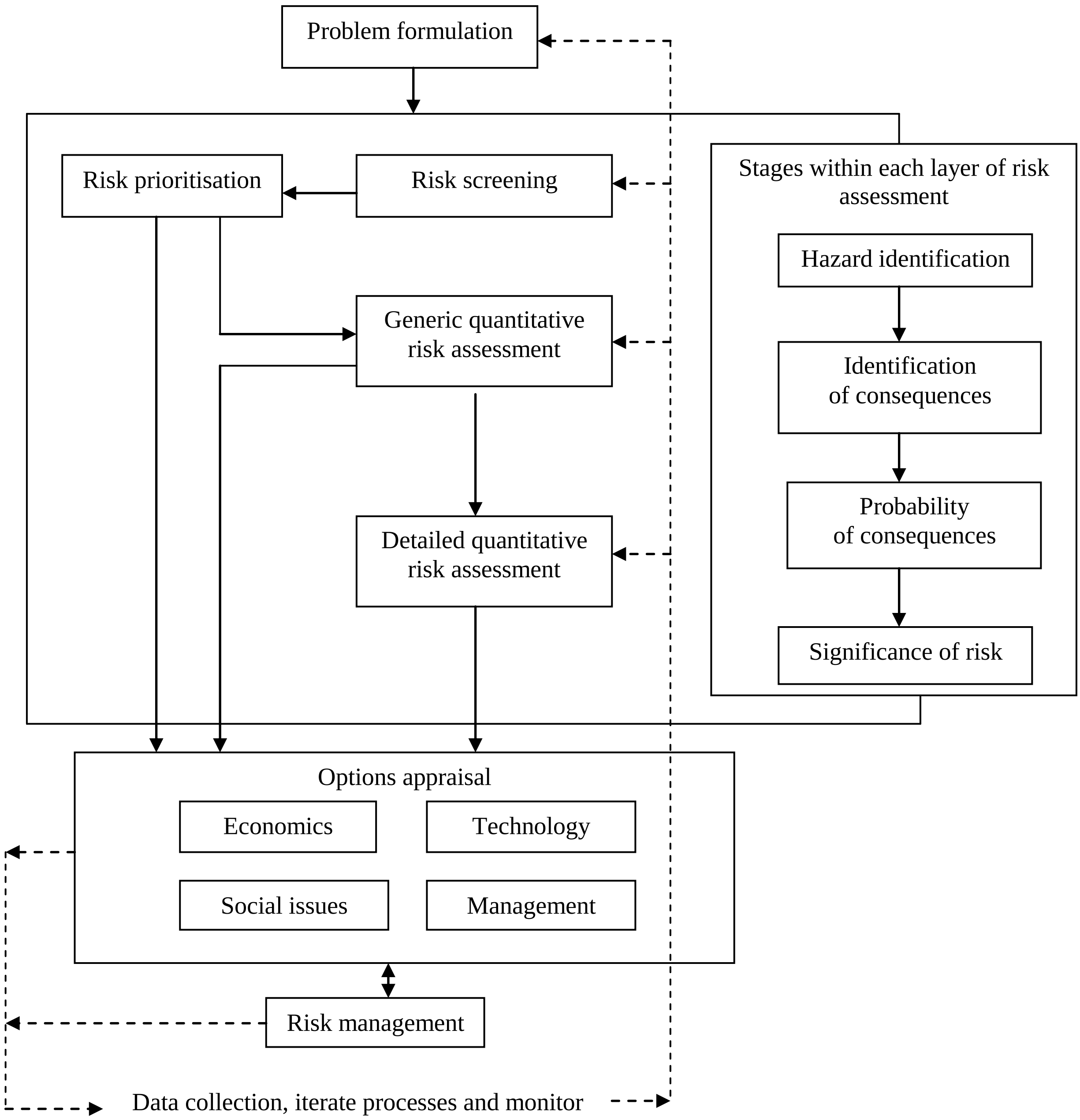

Fig.2.6. Framework of environmental assessment and management (adopted from: DETR, 1995)

2.2.3 Tolerability of risk

In order to reinforce sustainability in the case of hazardous waste materials, the environmental risk should be controlled and managed at an early stage. Furthermore, it is important to understand what the level of environmental risk (risk standard) ought to be by means of different risk assessment methodologies. This is especially implemented in hazardous waste site, consequently whether to take relevant measures to reduce and control risk. Therefore, it is necessary to set out a certain criterion to determine acceptable levels of risk (Bouder, Slavin and Lofstedt, 2008). The principle of "tolerability of risk" provides a framework by which judgments can be made as to whether society would accept the risk (HSE, 1988; Cowan 2005; Kumamoto 2007).

Importantly, this framework provides a benchmark for a tolerable risk, which cannot be deemed as broadly acceptable without implementing any risk control measures, see Fig.2.7. Tolerable risk is the gap between what is absolutely safe and absolutely unsafe, i.e. intolerable (Clay and Bassett 1999; Fuller and Vassie 2004). Between the intolerable region and the broadly acceptable region, it is a requirement to demonstrate the risk is 'as low as reasonably practicable' (ALARP), *i.e.* risk mitigation is in place. The ALARP principle was formulated by the Health and Safety Executive (HSE) (Smith, 2001; Manuele, 2003). Within the ALARP region, whether to reduce the level of risk further or accept the existing level of risk can be judged on the grounds of the risk levels and the costs associated with controlling the risk (Fuller and Vassie, 2004). The risk which is deemed as acceptable to society, should be lower than or at least below the upper boundary of ALARP region. This threshold is relevant to the "Basic Safety Level" (BSL), where the risk is most acceptable with the adverse consequence Society is prepared to accept. Thus, this level of risk is broadly acceptable and relates to "Basic Safety Objective" (BSO) (HSE, 1988). Compared with Fig.2.7, "frequency" and "harm" are comprised of a two dimensional area to set up the boundary between tolerable and broadly acceptable, which is better to present the variation of "tolerability of risk" (See Fig.2.8).

This principle is well established in some heavy industries, such as nuclear, chemical, *etc*. HSE has also proposed notional boundaries for each region (see Fig 2.9). A risk of death of 1 in 10^4 per annum to any member of the public is the maximum that should be tolerated from any large industrial plant in any industry. Moreover, HSE specifies that the maximum risk to workers in any industry should be tolerated is 1 in 10^3 per year. With the ALARP principle being implemented, the risk from most plant is in fact lower than the proposed boundary. The level of broadly acceptable risk is suggested as 1 in 10^6 per annum (HSE, 1988).

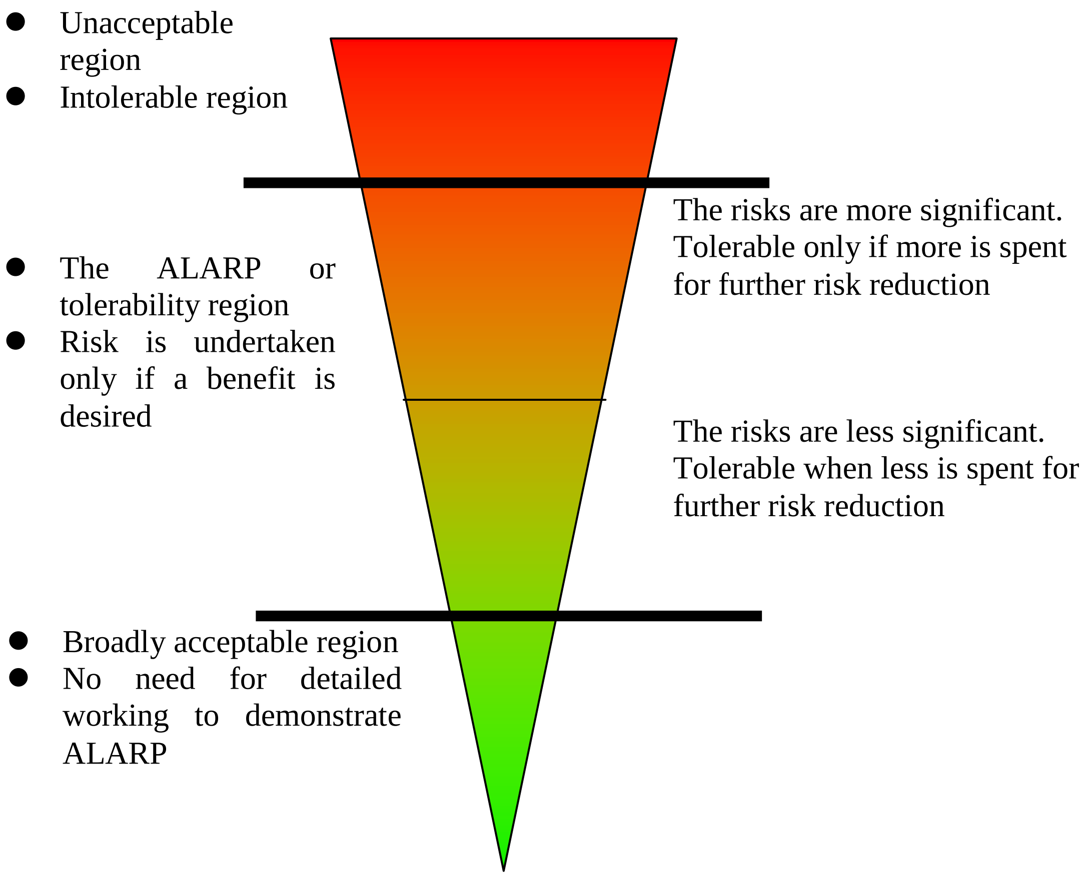

Fig.2.7. Tolerability of risk (Adapted from: HSE, 1988)

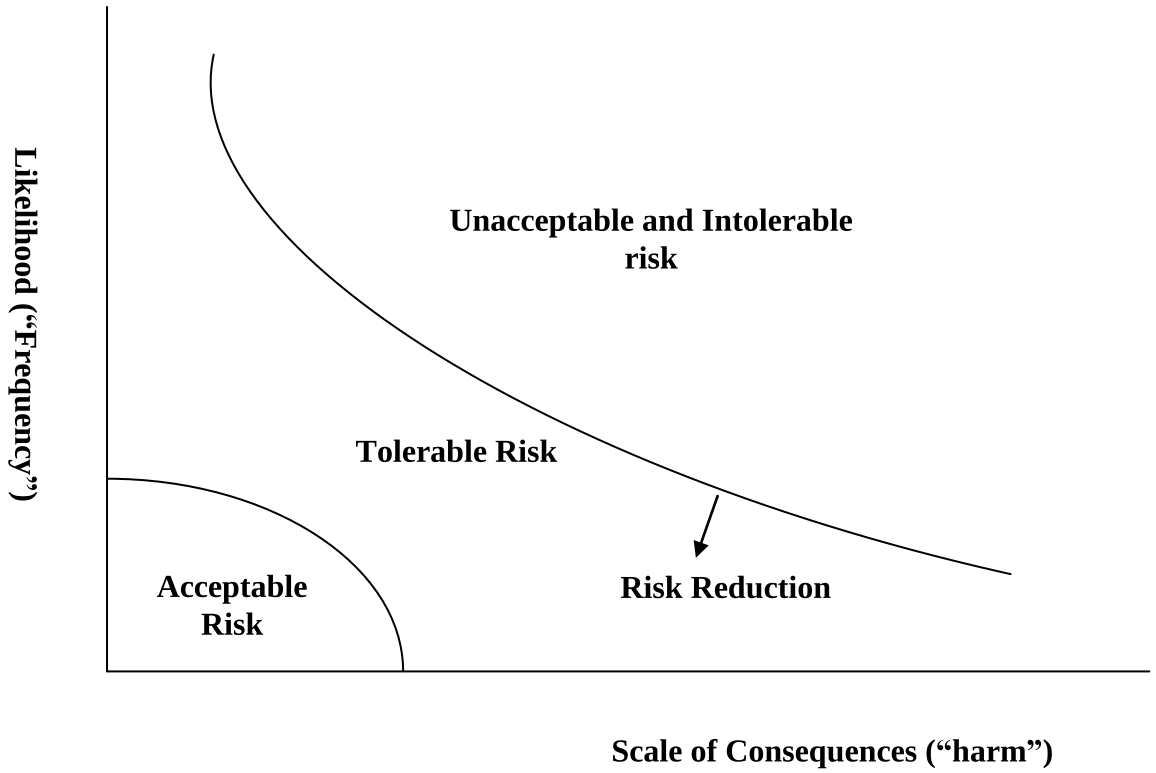

Fig.2.8. Another view of tolerability of risk

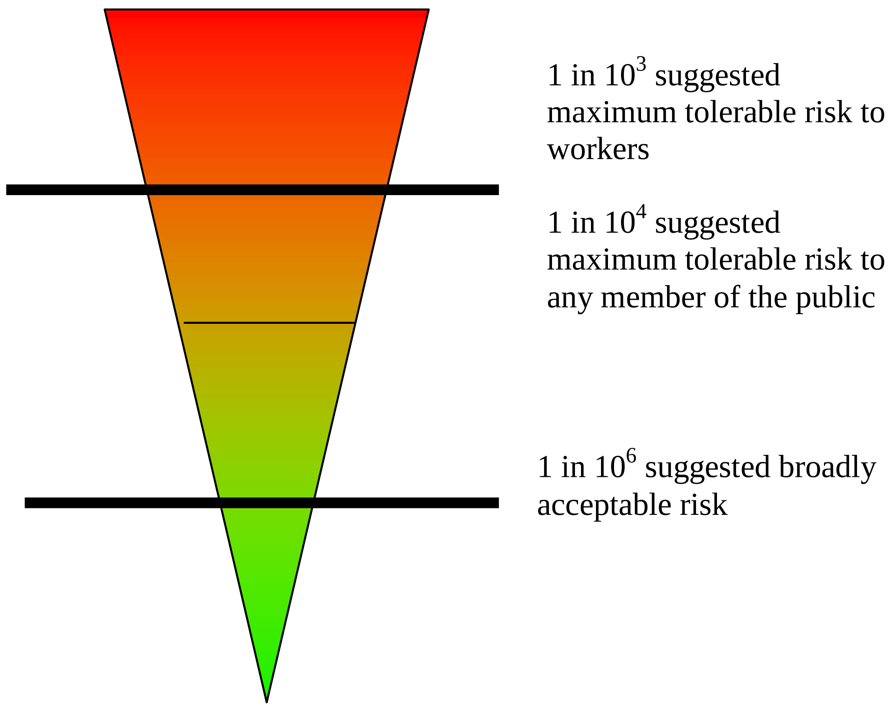

Fig.2.9. Tolerable and actual levels of risk to workers and the public (adapted from: HSE, 1988)

In the last few decades, a potential environmental risk has been identified as "Climate Change". This is generally acknowledged to be a global problem and thus to impede sustainable development (Markandya and Halsnaes, 2002; Hansjurgens and Antes, 2008). Previous studies have found out that greenhouse gas emission is a huge contribution to climate change (Solomon, Plattner, Knutti and Friedlingstein, 2008; Nerlich and Koteyko, 2009). For example, when waste materials are disposed in landfill, landfill gas, if uncontrolled, is considered as one of the main sources of greenhouse gas emissions, especially in producing large amounts of methane, which is about 21 times more potent than CO_2 (DEFRA, 2007). As there is no specific standard for carbon emissions in EU countries at present, it is unknown whether the risk "climate change" exceeds the upper limit of tolerability. However, it is proposed that the framework of "tolerability of risk" could be used to set up the criteria for carbon emissions reduction, which is presented in the Chapter 6. For instance, any CO_2 emissions may have an equivalent incremental risk analogous to the 'Tolerability of Risk', *e.g.* the tolerable/intolerable boundary of 10^{-6} deaths per year for the general public can be equated to a level of CO2 emissions from a product's lifecycle. Thus, a risk based analogy is then used to divide various regions or bands representing increasing levels of carbon emissions.

2.3 Carbon footprint

'*Carbon footprint*' is regarded as a new concept which has been widely adopted as "*the total set of greenhouse gas emissions caused directly and indirectly by a person, organization, event or product*" (Carbon Trust, 2009). As a response to the climate-change crisis, pressure is increasing societal responsibility to reduce and manage the carbon footprint. The carbon footprint calculation provides a tool to help conventional business gradually transform itself into a green business, especially reflecting in the following dimensions: environmental impacts of the supply chain, investment decisions in terms of the carbon profits, and strategies for product innovation to reduce the carbon emissions (Carbon Trust, 2006).

2.3.1 Carbon footprint measurement

The cornerstone of carbon labelling is the assessment of product carbon emissions following the principles of Life Cycle Assessment (LCA). A number of standards and protocols have been, and are still being, developed for this purpose. The ISO, the International Organization for Standardization, for example, has devised carbon emissions measurement standards. These include ISO 14067, still in progress, which will elaborate the requirements for the quantification and communication of the product carbon emissions (Gaussin *et al.,* 2011 In Press; Dias and Arroja, 2012). Additionally, the British Standards Institution (BSI) published the Publicly Available Specification (PAS) 2050 in 2008. The latter attempts to standardize methods for assessing the life cycle greenhouse gas (GHG) emissions for various goods and services, as well as specify the detailed requirements of the assessment (BSI, 2008; Sinden, 2009; Iribarren, Hospido, Moreira and Feijoo, 2010). In addition, the Greenhouse Gas Protocol Initiative was developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) as guidance to help organisations report their GHG emissions, (WRI/WBCSD, 2004; WRI/WBCSD, 2011).

Studies reported in the literature indicate that carbon emissions have been measured for a wide range of products using life cycle assessment methods. Iribarren, Hospido, Moreira and Feijoo (2010) used the ‘Cradle to Grave’ approach, by taking the full lifecycle of the product into account, to assess the carbon footprint of canned mussels from harvesting to ultimate disposal. This showed that 4.35 kilogram CO_2e (Carbon dioxide equivalent) were emitted per triple pack of round cans. Moreover, the primary packaging and mussel shell management were found to contribute the most to the carbon footprint taken over the whole lifecycle. Similar studies by Pathak *et al*. (2010) and Muthu, Li, Hu and Mok (2011), used life cycle analysis to measure the carbon footprint of food and shopping bags, respectively. The former study, relating to food production, examined 24 Indian food products, and showed that, for animal food and rice planting, methane was the main contribution to carbon emission, providing an opportunity for greenhouse gas (GHG) reduction by encouraging changes in current food consumption habits. With regard to the latter study on shopping bags, the IPCC 2007 method was applied to the carbon footprint calculation during the full lifecycle. This study compared the carbon footprint resulting from different disposal options for shopping bags, and confirming that reusing or recycling was preferable to landfill disposal. Similarly, in the case of beverages (juice, beer and water), Pasqualino, Meneses and Castells (2011) suggested that recycling was the optimal choice for disposing of packaging materials, depending upon the environmental impact (carbon footprint and energy consumption), whilst incineration and landfill were the near optimal choice. In addition, using life cycle assessment for carbon footprint calculation of milk production, Flysjö *et al.* (2011) found out some important factors which affect the carbon footprint, such as dry matter intake (DMI), emission factor (EF) for methane from enteric fermentation, amount of nitrogen applied and EF for direct nitrous oxide emissions from soils. If any of these parameters was altered, the total carbon footprint was changed correspondingly, by up to 15%.

2.3.2 Carbon labelling

The carbon emissions embodied in a product are usually presented to consumers in the form of a carbon label on product packaging. Carbon labels usually present emissions information either as in numerical form (*e.g.,* tonnes of CO2 emitted per product unit) or with claims of emissions reduction (Upham, Dendler and Bleda, 2011). Whilst the amount of literature is considerable on carbon footprint measurement, which can be viewed as the basis of carbon labeling communication, there is very little literature on carbon labelling itself (Upham, Dendler and Bleda, 2011). Edwards-Jones *et al.* (2009) investigated the vulnerability of exporting nations to the development of a carbon label. The carbon footprints of three vegetables, such as lettuce, broccoli and green beans supplied externally to the UK market were studied. This has highlighted export vulnerability in the areas of transport, the national economy and the supply chain network. Moreover, the geographically distant countries were identified most vulnerable, as their exports were substituted by the local UK products. Vanclay *et al.* (2011) examined the customers' response to carbon labelled products by recording the sales for a three month period. Thirty seven products were labelled with green, yellow and black footprints to represent their corresponding carbon emissions level, as below average, near average and above average, respectively. It was noted that customers' purchasing behaviour changed only slightly, with reduction of 6% in the case of the black labelled products, and an increase of 4% in green labelled products. Furthermore, Upham, Dendler and Bleda (2011) discussed the public perceptions of carbon labelling of grocery products, and found that the emission value, without further explanation, cannot significantly influence product selection. A similar study can be found by Gadema and Oglethorpe (2011), who surveyed the purchasing habits and perceptions related to various carbon labelled food products. Although the surveyed consumers displayed a high preference motivation (72%) for carbon labelled products, a high proportion (89%) were confused by carbon labels resulting from different interpretation or comprehension. While previous studies are very useful in informing our approach, none of them focuses on how to improve the carbon label itself to be more readily understood by consumers. Even though a previous study has proposed using the normalization approach for processing the data from life cycle assessment (Upham, Dendler and Bleda, 2011), it is still a conceptual idea, and how to normalize the carbon footprint value and establish an appropriate frame of reference have not been addressed anywhere. It is hoped an improvement in the clarity of current carbon labelling schemes is essential, and thus encourage consumers to select low carbon products, and so increase the potential for reduction in carbon emissions.

2.4 Game theory

Since von Neumann and Morgenstern (1944) published their book "The Theory of Games and Economic Behavior", game theory has been widely used as a mathematical and logistical approach applied in various research fields, such as economics, marketing, supply chain *etc*. Game theory models can be used to test against real human behaviours, and the solutions are usually arrived at by considering the interaction between the 'players' (or 'agents' in the context of the supply change) who are involved, which can be seen as a form of "interactive decision theory" (Aumann, 2003; Pak and Brieva, 2010). In general, the role of game theory in academic research is to help 'players' decide their own strategies by predicting the actions of other players based on the expectation of the maximized payoff (Madani, 2010).

With natural resources being exploited at an increasing rate, the conflict over resource extraction and allocation, pollution control and management *etc* becomes more and more fierce. Thus, game theory has become an essential tool for the analysis of environmental problems (Hanley and Folmer, 1999). In the following sections, game theory application to environmental policy, supply chains and green supply chains, waste management are reviewed, respectively.

2.4.1 Application of game theory to environmental policy

In the field of environmental policy, game theory is used to analyse how such policies affect the decision-making of different ‘players’ and provides a useful insight to increase the stability of policies aimed at improving environmental management and regulation (Albiac, Sánchez-Soriano and Dinar, 2007). Endres and Finus (1998) have established a bargaining game of incomplete information to investigate how the policy affects pollution control, in order to reinforce the stability of international environmental agreements. Three policy frameworks such as ‘emission reduction quotas’, ‘effluent taxes’ and ‘tradable emission’ have been investigated to derive the socially optimal emission levels and Nash equilibrium emissions. Similarly, Feenstra (1998) has built a dynamic game model to analyse the environmental policy set by national government that balance environmental standards with domestic firm competitiveness in the context of international trade and transboundary pollution. The Governmental role seems not only to arouse the vitality of domestic firms, but also improve environmental quality. Thus, the relevant policy instruments should balance the two aims, in which ‘emission taxes’ and ‘emission standards’ are compared in this game model. Only if the taxes and standards are equivalent, environmental policy can be set at a laxer level. With regard to the resource management policy, Munro (2007) has investigated the problem of the management of shared fishery resources by means of game theoretical analysis, which can be reflected in the strategic interaction of resources shared between different States. In this case, game theory could derive the necessary conditions for stability of a new regime. However, game theory applications for policy making or analysis in cleaner production have been rarely reported in the literature. A typical study can be found by Dong *et al.* (2010), who have built a game theoretical framework to analyze the conflicts between local government and a polluting firm, whist promoting cleaner technologies in the Chinese electroplating industry. Such policy variables as 'psychological costs', 'environmental benefit evaluation', 'reward local government for its implementation' have been discussed in the game model. Most of these previous studies present game theoretical analysis in an abstract way, based upon mathematical models or frameworks, in the form of equations containing many parameters. The messages derived from such complex analyses can be poorly understood by policymakers.

2.4.2 Application of game theory to supply chains

In the supply chain field, game theory is usually used as a tool to deal with supply chain management problems with multiple agents, often with conflicting objectives, in order to help decision makers enhance the cooperative efficiency of the partners involved in the supply chain or in the design and construction of new supply chains (Cachon and Serguei, 2004). Game theory application in supply chain coordination can be divided into two areas of application: the cooperative game and the non-cooperative game. For the cooperative game, Li, Huang, Zhu and Chau (2002) developed three game models to determine the optimal cooperative advertising program between a retailer and a manufacturer in order to achieve the full coordination of the supply chain, where influencing factors such as 'brand name investment', 'local advertising' and 'sharing policy' were discussed. Further, Yue, Austin, Wang and Huang (2006) analyzed profit sharing between a retailer and manufacturer making the assumption that the manufacturer provides price deduction to the customers, and suggested that the profits could be increased for both parties when they coordinated as a partnership relationship in cooperative advertising. Nagarajan and Sosic (2008) used cooperative bargaining models to investigate the economic profit allocation between different supply chain partners, and then discussed the profit stability based upon their potential coalition. However, for the non-cooperative game, Wang, Guo and Efstathiou (2004) discussed a decision model between one supplier and n retailers in echelon inventory games and local inventory games. Later Esmaeili, Aryanezhad and Zeephongsekul (2009) built both cooperative and non-cooperative game models between the sellers and buyers across the supply chain. Hennet and Arda (2008) studied the efficiency of different types of contracts subscribed by the participants of the supply chain. Leng and Zhu (2009) developed a side-payment contract scheme for the supply chain coordination and for reducing the impact of forward buying on supply chain performance. However, these studies mainly focus on the economic stability or the supply chain efficiency. None of them has applied game theory approach to discussing environmental issues.

2.4.3 Application of game theory to green supply chains

Game theory applications for 'green' supply chain management have been rarely reported in the literature. Zhu and Dou (2007) have created a game between government and enterprises in the green supply chains and such factors as cost and benefit, governmental subsidies and penalties have been investigated. The game result suggests that government should reinforce the environmental regulations by means of increasing relevant subsidies and penalties to impel enterprises to implement environmental management. Chen and Sheu (2009) have applied game theory to the design of environmental regulation pricing strategies. With the governmental regulation standards being raised, manufacturers will gradually extend their product responsibility followed by increasing the product recyclability. Further, Sheu (2011) has used the asymmetrical bargaining game model to seek to negotiate solutions between manufacturers and the 'reverse logistics' suppliers under the governmental financial intervention, from which the bargaining power of green supply chain members will be greatly affected. A similar study can be found by Barari *et al.* (2012), who have provided a dynamic evolutionary game model to discuss the potential strategic coordination between producer and retailer by maximizing economic profits while implanting green practices, thus to achieve a 'win-win' situation between environmental and commercial benefits on the supply chain. These past studies are very useful in informing our approach, however they do not consider the issues raised in the introduction, namely, by identifying which producers offer a sustainable economic performance with a level of environmental risk or carbon footprint which society is prepared to accept.

2.4.4 Application of game theory to waste management

At present, studies of Game theory application to waste management are rarely reported in the literature. Cheng, Chan and Huang (2003) have put forward multi-criteria decision analysis (MCDA) integrated with inexact mixed integer linear programming (IMILP) to select the appropriate landfill site to minimize the total cost of waste management. Moreover, co-operative game theory is used as a sub-module of MCDA to evaluate the landfill site alternatives. Davila, Chang and Diwakaruni (2005) have used a two-tiered grey integer programming based on the game theoretic analysis to evaluate the optimal pricing strategies for tipping fees available to certain regional landfills. The game model is derived from a "Two Person Zero-Sum" game, and the corresponding payoffs matrix is constructed by the grey integer programming algorithm. Thus, different strategy "win or lose" can be compared by the payoffs matrix while taking the relevant constraint conditions into account, *e.g.* economic cost, design capacity *etc.* For example, Fig.2.10 shows that payoffs (nodes) resulted from a step reduction in tipping fees at Edinburgh and Browning-Ferries Industries (BFI) landfills (E_n for Edinburgh, B_m for BFI).

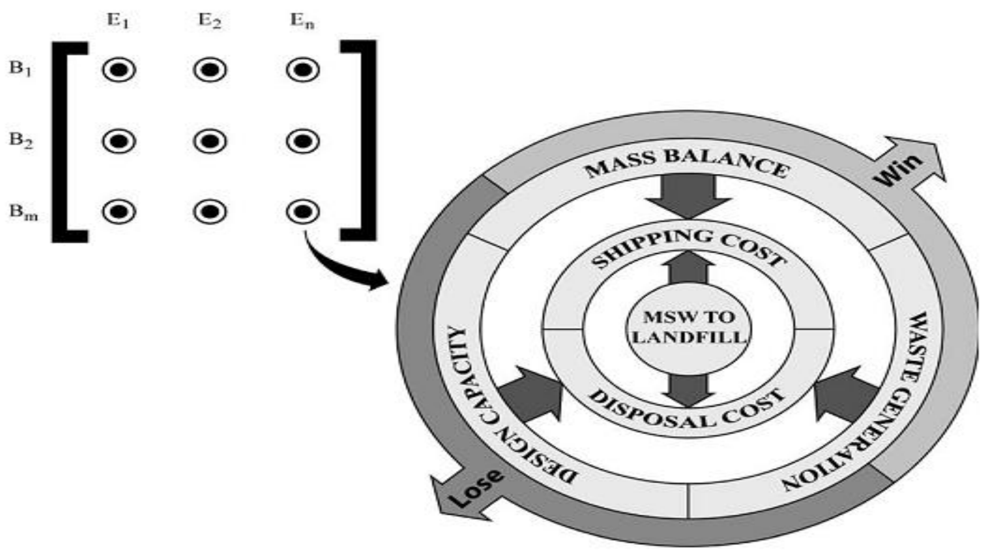

Fig.2.10. Strategic actions selected by the payoffs matrix and constraint conditions (adopted From: Davila *et al.,* 2005)

Grimes-Casey, Seager, Theis and Powers (2007) have integrated game theory with the lifecycle cycle assessment (LCA) of bottle packaging to discuss the preferable choice between refillable and disposable bottles. The refillable bottles can be reused only if the consumers maintain high return rates and the consumers who keep the refillable bottles may raise the reusing cost. Therefore, the optimal strategy is expected to be cooperated between the bottlers and consumers. Jørgensen (2010) has created a dynamic game scenario for waste management. This game prototype is derived from a "N-Person

Cooperative” game, where there are three players involved. Each player has a stock of waste, and would dump a certain amount to another player at any instant of time. Assume that the overall waste constant throughout the game scenario, the region’s stock of waste can be reduced only by dumping on others. The analysis shows that an inter-temporal core-theoretic cooperation can be sustained in a finite time horizon.

2.5 Decision support systems

Since the 1970s, research into decision support systems (DSS) has occurred in a range of fields, *e.g.* finance (banking, insurance). A DSS can be defined as an integrated approach, in the shape of computer-based information system, which promotes practical problem solving at the beginning of the process, and then supports decision-making activities during the implementation stages (Stuth and Lyons, 1993; Power, 2002). With DSS technology development in recent years, it has been widely used in the sustainable development study for decision-making, such as land and water management; food production and distribution; poverty alleviation; public health services; environmental management; pollution control; urban planning and management; economic planning; recovery from natural disasters *etc* (Mikolajuk and Yeh, 2000). The development of decision support systems for hazardous materials/waste has gone through several important stages, such as conceptual prototype; model design oriented application and computer based system respectively. Present studies mainly focus on the decision support systems application to hazardous materials/waste management at the stage of transportation or final disposal. However, none of them has discussed the stage of waste reduction or prevention.

2.5.1 Decision support system for hazardous materials transportation

In the past 20 years, decision support system has gradually evolved from a conceptual model to a computer based system. Bowen, Weeks, Batra and Hill (1989) have established a framework of decision support system to evaluate nuclear waste trans-shipment in order to determine a low risk and cost route. The framework is a two-tier system, which is comprised of the model database and the user interface. Moreover, the model database contains a routing model, transportation model and decision-tree model separately. Each model is one mathematical programming problem, see Fig.2.11.

Further, Beroggi and Wallace (1994) provided a prototype DSS for operational control of hazardous material shipments by means of hypermedia technology. The main function of this DSS was to help operator at a control centre monitor transportation process of hazardous materials in real time, especially in helping vehicles assess the route condition risk and select the most cost-effective routes. Zografos, Vasilakis and Giannouli (2000) put forward a decision support framework by choosing appropriate operations management for hazardous materials emergency response, especially for large scale industrial accidents in Western Attica, Greece. There were several prominent features of the methodological framework to establish better communication for hazardous emergency response operations, such as providing the capability to identify different roles and responsibilities, developing procedures for the integrated functions, as well as establishing the continuous interaction between developers and users through a series of acceptable models.

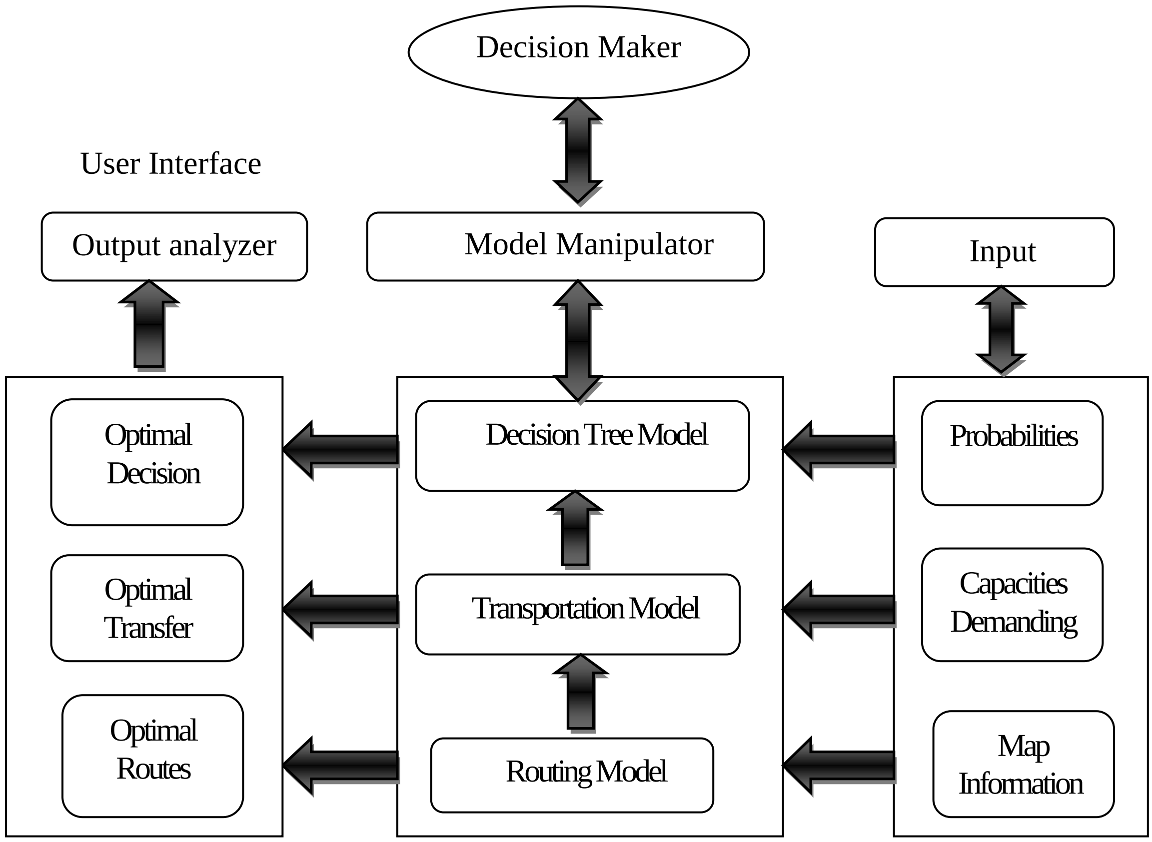

Fig.2.11. Structure of the proposed decision support system (adapted from: Bowen *et al.,* 1989)

On the basis of the above methodological framework, Zorgrafos, Androutsopoulos and Vasilakis (2002) developed a real-time DSS for roadway logistics and incident response, aimed at minimize the response times to any incidents. Several important functionalities were provided by this DSS, such as districting, response unit dispatching, routing of response units and on scene management. Similar work was undertaken by Hamouda (2004) to support emergency response planning in which a DSS was proposed to integrate the hazardous materials transport risk analysis with the emergency response and allow the assessment of implications with regard to the regional locations of hazardous materials teams. Bubbico, Di-Cave and Mazzarotta (2004) introduced the application of geographic information system (GIS) for decision support of hazardous materials in terms of risk analysis for road and rail transport, and considered factors that affected the risk analysis, *i.e.* population, accident rate and weather conditions along the transport route. By means of the database of GIS, risk curves can be derived for different transport scenarios and the possible consequences resulted from changes of transportation routes or modalities can be investigated rapidly, so as to achieve comprehensive risk management for hazardous materials transportation. Gheorghe *et al.* (2005) designed a DSS in a software platform, through the application of 'hot spot approach', using intelligent maps and GIS for hazardous materials rail transportation risk analysis. The determination of the annual societal risk resulted from the specific sudden accident scenario was provided, and moreover the potential causes of an accident was revealed while taking the spatial parameters into account. Similar works can also be found concerning DSS design for hazardous materials transportation, through which risk analysis is the most paramount element (Madala, 2000; Qiao, 2006). In addition, Zografos and Androutsopoulos (2008) integrated routine and emergency decisions together, and designed a DSS based on GIS to determine the non-dominated hazardous materials distribution routes whilst minimizing the economic cost and risk, and so were able to allocate the emergency service units to achieve timely response once accidents had happened, and predetermine the shortest evacuation path from the impacted area to the designated safety area (See Fig.2.12). Further, Zhao, Liu and Li (2012) designed an environmental risk information management system for China Railway Ministry. This system aimed at reducing the serious consequence resulting from sudden environmental pollution accidents during hazardous materials rail transportation, by means of computational simulation techniques for different accident scenarios, *e.g.* poisonous gas diffusion. Moreover, this system was incorporated transportation management of hazardous materials and consequent environmental risk into the design approach, using techniques of Management Information System (MIS) and geographical information system (GIS) for system development.

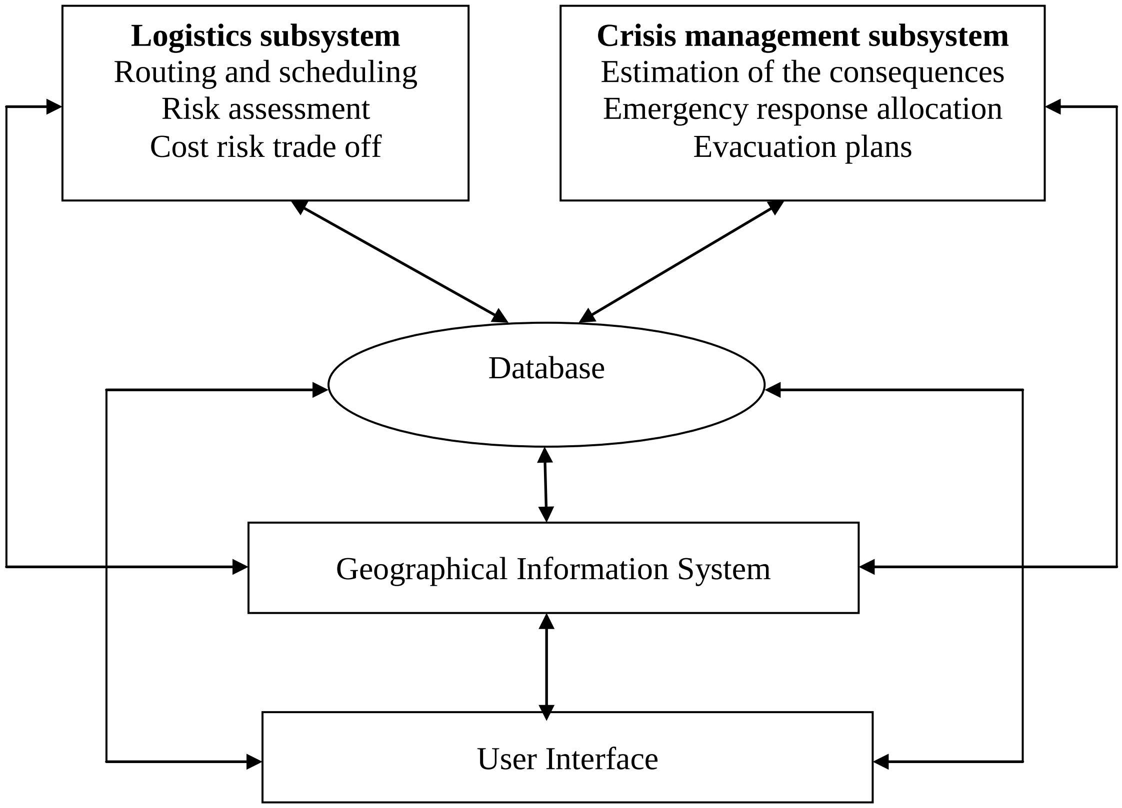

Fig.2.12. Architecture of the decision support system
(Adopted from: Zografos *et al.*, 2008)

2.5.2 Decision support system for waste management

Decision support system could be beneficial for the decision makers in the field of waste materials management to find out optimal or near optimal decisions (Finlay, 1989).

Paige, Stone, Lane and Hakonson (1996) designed a prototype based upon multi-objective decision theory to help engineers or designers select an appropriate trench cap for waste disposal. They used the hydrologic evaluation of landfill performance (HELP) model integrating with chemicals, runoff and erosion from agricultural management systems (CREAMS) to simulate the trench cap water balance and erosion, separately. Further, Boyle and Baetz (1998) developed a conceptual prototype to select the appropriate management options for various wastes from one or more industrial plants. In particular, the potentials for reusing and recycling waste materials, as well as pre-treatment and co-treatment before final disposal were determined. The novel idea in this conceptual design was that the options were more efficient to recycle the useful waste materials and recover the waste energy, by using 'trains' (sequential approach) for waste materials sorting and treatment (see Fig.2.13).

With the development of information technology, there are a number of decision support systems designed for municipal waste management to determine the optimal plan for waste collection, treatment, disposal capacity and sites allocation *etc*, by means of computer based techniques, some of which have been implemented by case studies, to demonstrate their availability. Chang and Wang (1997) developed an environmental decision support system for regional municipal waste management in Taiwan, based on a software package 'SAS@'. Haastrup *et al.*, (1998) built a decision support system for regional waste management in Sicily, to identify the areas which are suitable for waste treatment and optimize the selection of disposal location. The related studies can be found by Fiorucci, Miniciardi, Robba and Sacile (2003), Simonetto and Borenstein (2007), in which the former mainly focused on the determination of optimal quantities and characteristics of waste materials sent to the different disposal facilities, *e.g.* landfill, recycling centre *etc*, based upon a constrained non-linear optimisation problem, with cost minimization including recycling, transportation and maintenance cost. The later one concentrated on the solid waste collection process, by building an operational planning system called "Solid Waste Collection Decision Support System" (SCOLDSS) to implement in Porto Alegre, Brazil. This system was consist of several functional modules, such as allocation of collection vehicles, transportation route selection, predetermination of daily amount of waste sent to the sorting units.

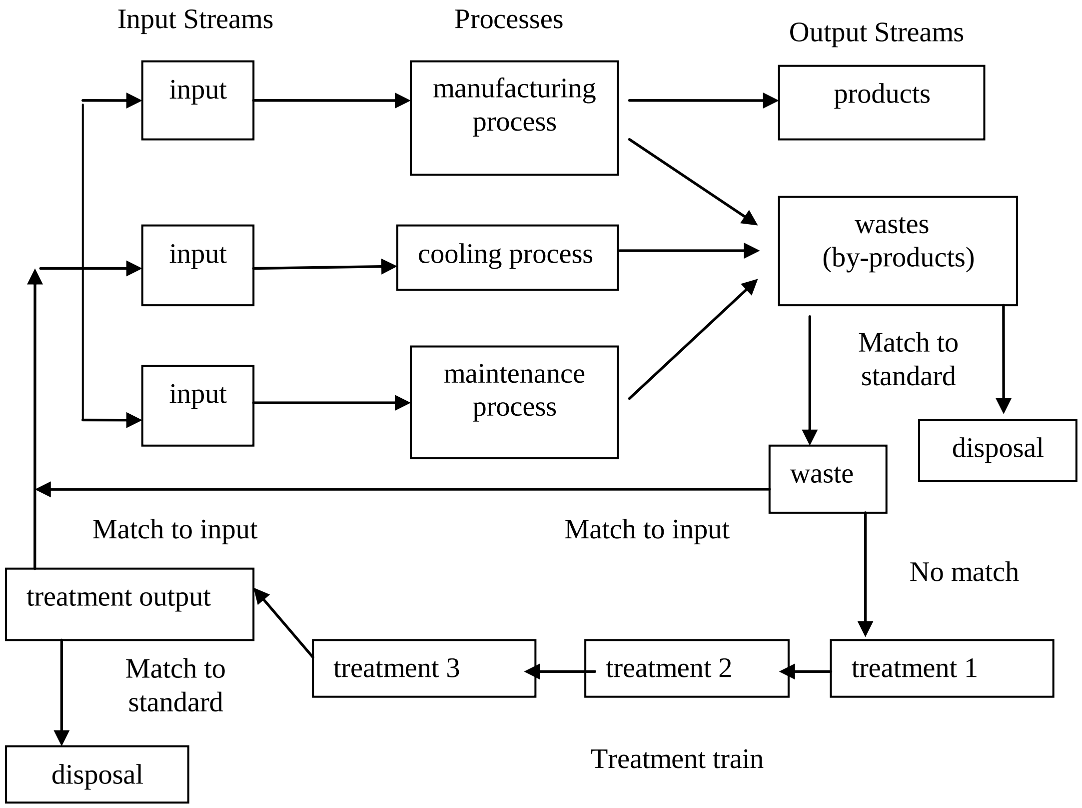

Fig.2.13. Conceptual prototype of decision support system for industrial waste (adopted from: Boyle and Batez, 1998)

In the context of sustainable development, life cycle assessment has been widely integrated with optimisation methods such as 'cost-benefit' analysis, multi-criteria decision analysis *etc.*, for decision-making in the field of municipal or hazardous waste disposal management. Costi, Minciardi, Robba and Rovatti, (2004) proposed an environmentally sustainable decision support system for urban waste management, which was based on a constrained non-linear optimisation problem by taking the economic costs, technical and environmental factors into account, to determine the allocation of waste materials by sending to the different disposal facilities, *i.e.* recycling centre, incineration plant, sanitary landfill. A similar study was found by Oropeza (2006) in his Ph.D dissertation "SUWAMAS, a decision support model for sustainable waste management systems". SUWAMAS represented 'Sustainable Waste Management

System', developed by an integer non-linear mathematical programming, which was comprised of four functional modules to achieve waste sustainability, being not only economically affordable, environmentally effective, socially acceptable but also logistically optimised (see Fig. 2.14). Five waste disposal operations were considered in this proposed system, as mechanical, biological, mechanical-biological recycling, incineration and landfill, respectively. The results were also to determine the optimal flow distribution of primary and secondary waste, thus to decide the number and location of the corresponding waste disposal facilities. In addition, the shortest paths between waste generation sites and the treatment facilities were provided by the system.

Further, Boer, Boer and Jager (2007) designed a decision support tool for sustainability assessment of waste management systems, in which four different scenarios were considered, *i.e.* temporary storage, collection and transportation, treatment and disposal. This system also incorporated the economic, environmental and social sustainability into integrated evaluation criteria. However, it should be noticed that the assessment results were displayed separately, instead of converting the outcomes into a normalized unit. Minciardi, Paolucci, Robba and Sacile (2008) used the non-linear multi-objective approach to develop a decision support system for sustainable waste management, whilst minimizing economic costs, un-recycled waste, and quantities of waste sent to the landfill and environmental impact caused by the incineration.

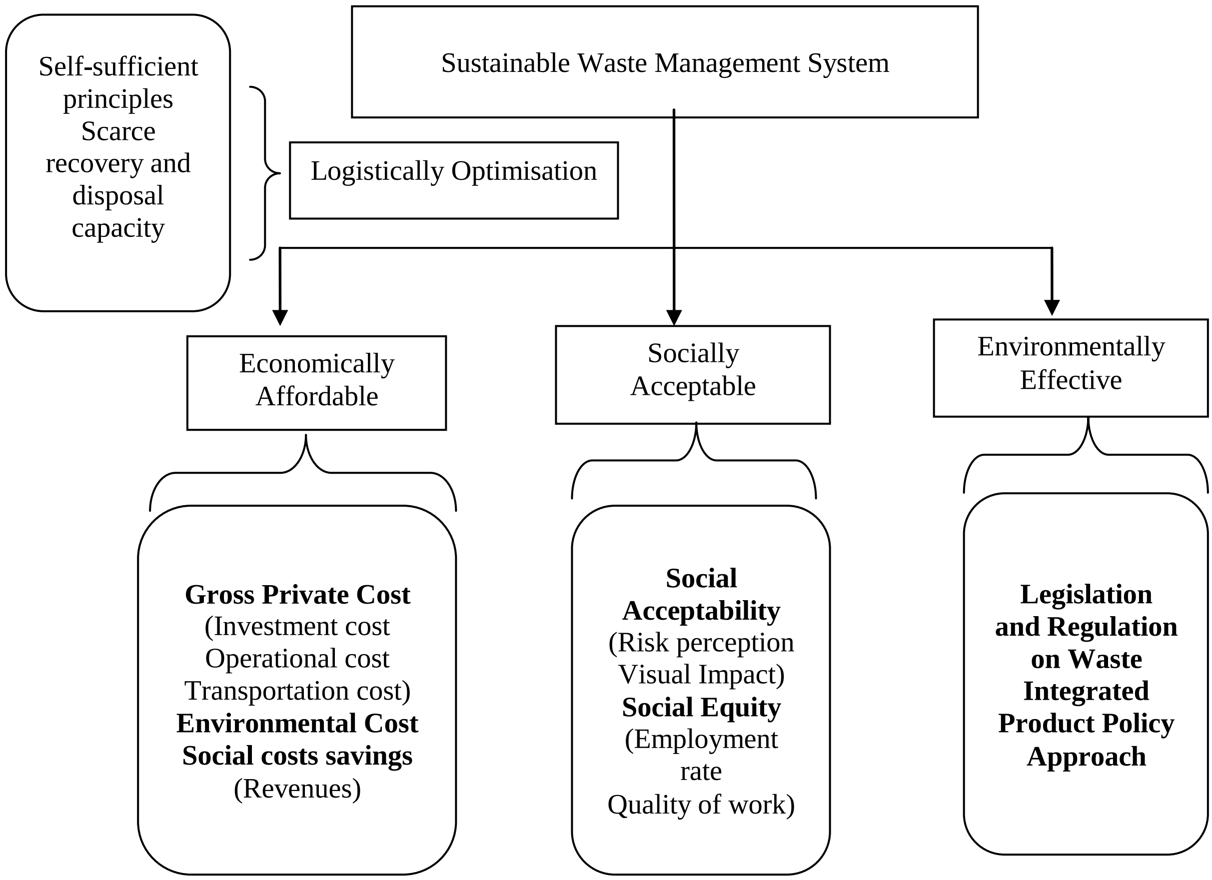

Fig.2.14. Assessment criteria of sustainable waste management system (adopted from: Oropeza, 2006)

2.6 Summary

This Chapter has reviewed the previous studies on hazardous materials/waste management, environmental risk, carbon footprint, game theory application, and decision support system, which are very useful in informing this research to develop a novel environmental risk management system for hazardous waste materials.

In order to manage the waste materials more efficiently, it is proposed that product lifecycle management combined with the waste management, and risk management to reduce their inherent risk and environmental impact throughout the product lifecycle, *i.e.* design, production, transportation, use and final disposal. Moreover, 'cleaner production' has been demonstrated as the best model for pollution prevention within product life cycle management. In this context, materials selection plays an important role to promote cleaner production, whilst providing better and safer products for the public. However, most of these previous studies have concentrated on selection between different materials. Selecting from a range of materials of a similar type and composition still has not been discussed.

Environmental risk and carbon footprint are two significant indicators in the product lifecycle management. Previous studies have mainly focused on risk management on human health resulted from the hazardous materials/waste including the stages of production, transportation and disposal. However, there is no connection between risk and carbon footprint (which has been deemed as a potential environmental risk, see Section 2.2.3). Although HSE has put forward the framework of "tolerability of risk", by which judgments can be made as to whether society would accept the risk or not, there is no specific criteria for carbon emissions in EU countries. Thus, how to set up the appropriate criteria for carbon footprint reduction is suggested and discussed in this study (See Chapter 3 and 6). Whilst studies reported in the literature indicate that carbon footprint have been measured for a wide range of products by using life cycle assessment, which can be viewed as the basis of carbon labelling communication, there is very little literature on carbon labelling itself. This study proposes an improved carbon labelling scheme to appreciate the significance of a product's carbon footprint in a more visual way, as presented in Chapter 3.

With regard to the game theory, it has been widely employed in economic, market and environment research to aid decision-making by considering the interaction between the 'players'. Although studies have reported in the literature that game theory has been used for environmental policy making, the application to analysis in the context of ‘cleaner production’ have been rarely reported. Most of these previous studies present game theoretical analysis in an abstract way which can be poorly understood by policymakers. This study will employ a software package to intuitively demonstrate the possible game actions between government and manufacturer in the context of cleaner production, presented in Chapter 5. Moreover, none of the previous studies have applied game theory to discussing a level of environmental risk or carbon footprint reduction in the context of ‘green supply chain management’. Therefore, using game theory could provide a novel insight to provide optimal strategies for decision-making in this study, thus to reduce the environmental impact, which are described in Chapter 6 and 7.

Past studies on decision support system for hazardous materials or waste have mainly focused on the transportation and disposal stage, including the application of shortest transportation paths determination, waste option selection, waste facilities allocation *etc*. However, none of them has involved the stage of waste reduction or prevention and none has used game theoretical analysis to aid decision support for hazardous waste materials management.

Chapter 3: Carbon Emissions Intensity Ratio[2]

3.1 Introduction

With the issue of global climate change assuming a higher profile in the socio-political context, greater attention is being paid to the greenhouse gas emissions produced by goods and services, directly and indirectly during their lifecycle (Wiedmann and Minx, 2007; Iribarren, Hospido, Moreira and Feijoo, 2010). Business management, in the UK and elsewhere, has been encouraged, and in some instances required, to measure and report carbon emissions to incentivise and monitor emissions reductions (*e.g.,* DEFRA, 2009). For manufactured goods environmental interventions, such as emissions reductions, need to be implemented mainly through product design and innovation (Deutz, Neighbour and McGuire, 2010; Song and Lee, 2010). Moreover, with the concept of 'green' consumerism emerging gradually into the market, consumer preference may be also influenced by information provided through carbon labelling of products (Vanclay *et al.,* 2011). The UK government launched the carbon labelling program in 2007, and now more than 1100 products have been carbon labelled (Tesco, 2011). A Recent investigation shows that some UK customers can be persuaded to buy a product with low carbon emissions, given the relevant information, 59% of people surveyed had selected at least one carbon-labelled product during the previous three years (Tan, 2009; Tesco, 2011).

The carbon emissions embodied in a product are usually presented to consumers in the form of a carbon label on product packaging. Emissions information is typically presented either in numerical form (*e.g.,* tonnes of CO_2 emitted per product unit) or with

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[2] This chapter has been published by the Journal "Environmental Research Letters". See details in: Zhao, R., Deutz, P., Neighbour, G., McGuire, M., 2012. Carbon Footprint Intensity: an Indicator for Improved Carbon Labelling Scheme. *Environmental Research Letters* 7, 01414.

claims of emissions reduction (Upham, Dendler and Bleda, 2011). A typical carbon reduction label has been developed by the Carbon Trust. The label presents the life cycle carbon emissions of the product per functional unit (*i.e.,* packet, or serving), which the Carbon Trust define as the carbon footprint (www.carbontrustcertification.com; accessed 31/10/2011).

Fig.3.1 shows an example of a typical carbon label developed by the Carbon Trust, in which '100 g' indicates the carbon footprint throughout the product's lifecycle, in terms of the mass of 'CO2' carbon dioxide emitted, or its equivalent of other greenhouse gases, and 'per serving' helps the consumer to relate a typical quantity of food to its carbon footprint (Carbon Trust, 2010).

Fig.3.1. Carbon reduction label in UK (Adopted from: Carbon Trust)

The carbon label is seen as an effective means of communication to raise consumers' awareness of climate change, and thus to help change their lifestyles and purchasing behaviours (Carbon Trust, 2008; Tan, 2009). However, based upon the responses from focus groups and surveys of responses to carbon labelling, it is clear that the public find it quite difficult to imagine a given quantity of CO_2 emission and its potential environmental impact (Upham, Dendler and Bleda, 2011; Gadema and Oglethorpe, 2011 in press). In this context, the current system of carbon labelling does not communicate a sufficiently meaningful message to the consumer, especially if the label simply presents the emissions value on the product package.

Thus, the carbon label still needs further improvement, in order to establish an appropriate frame of reference that helps consumers better understand the concept of a carbon footprint (Carbon Trust, 2008). This Chapter proposes a dimensionless system of carbon emissions labelling, which, by facilitating comparison between products, would increase the ability of green consumers to implement their concerns in the market place. The carbon emissions data are normalized to a common scale of Carbon Emissions Intensity (CEI), and a new indicator Carbon Emissions Intensity Ratio (CEIR) is generated based the ratio of CEI to the annual national greenhouse gas emission per gross domestic product. The value of the dimensionless Carbon Emissions Intensity Ratio (CEIR) of a product can be evaluated on a simple scale with five ranges of values from ‘extremely low’ to ‘extremely high’. The performance of a given product can be presented on its packaging by a simple diagram with colour gradation. It is hoped that this study could lead to an improvement in the clarity of current carbon labelling schemes and thus encourage consumers to select low carbon products, as well as increasing the potential for reduction in carbon emissions.

3.2 Methodology

Carbon emissions derived from the LCA is generally determined by functional unit. That is the carbon emissions relate to a specific scenario, *e.g.* per pack, per serving, per pint *etc* (Carbon Trust, 2010). The starting point of the proposed methodology is to normalize the carbon emissions into a common scale. Here, it is considered using an indicator defined as 'Carbon Emissions Intensity' (CEI), which can be understood as carbon emissions per unit of economic output (DEFRA, 2009). This indicator can be calculated as follows:

$$CEI = \frac{CE_i}{R_i(j)} \tag{3-1}$$

where CE_i is the carbon emissions of the ith product (kilogram per functional unit), which is derived from a LCA; $R_i(j)$ is the retail price of the ith product at the the jth year, using British pounds per functional unit.

However, the CEI is highly dependent upon the retail price, fluctuations of which would disguise temporal variations in carbon emissions levels (DEFRA, 2009). Thus, in successive years the product's retail price would need to be adjusted to allow for inflation. This is not a trivial matter, but the UK government, for example, provides guidance on the derivation of official measures of inflation, as well as tracking the calculated values (Office of National Statistics: www.ons.gov.uk/ accessed 8/1/2012).

The second stage is to devise a baseline to build a dimensionless indicator and frame of reference. The baseline is the national carbon emissions per unit of gross domestic product (GDP), defined as National Carbon Emissions Intensity (NCEI) (Fan *et al.*, 2007; Wang, Wang and Wang, 2011 In press). This is expressed as follows:

$$NCEI(j) = \frac{GHG(j)}{GDP(j)} \tag{3-2}$$

where $NCEI(j)$ is the National Carbon Emissions Intensity for the country of production in a designated year (j); $GHG(j)$ is the national greenhouse gas emissions (direct emissions) at the jth year and $GDP(j)$ is the national gross domestic product at the jth year. The NCEI is based on estimated emissions for a given year, rather than life cycle emissions for a product. This is appropriate as an emissions intensity baseline is established in time, to facilitate comparison of product emissions intensity over time, as well as between products at a given time.

From Equations (3-1) and (3-2), a dimensionless indicator can be set based upon the ratio of CEI and NCEI, which now can be defined as the 'Carbon Emissions Intensity Ratio' (CEIR) and expressed as follows:

$$CEIR_i = \frac{CEI_i}{NCEI(j)} = \frac{\frac{CE_i}{R_i(j)}}{\frac{GHG(j)}{GDP(j)}} = \frac{CE}{R_i(j)} \times \frac{GDP(j)}{GHG(j)} \qquad (3\text{-}3)$$

By definition, the value for NCEI for the designated baseline year would remain constant for the calculation of CEIR for successive years. Thus any change in CEIR over time would be accounted for primarily by changes in carbon emissions per product unit for the given product. It is assumed in this proposed methodology that CEIRs are normally distributed with mean value μ and standard deviation $\pm\sigma$. This assumption may be compromised if, for example, products for which data are available are preferentially from higher emissions categories. However, this potential problem would decrease over time, as labelling became more widely adopted. Based on this assumption, it is proposed to divide the carbon emissions intensity ratio into five ranges, designated as extremely low, low, medium, high and extremely high, respectively (See Fig.3.2).

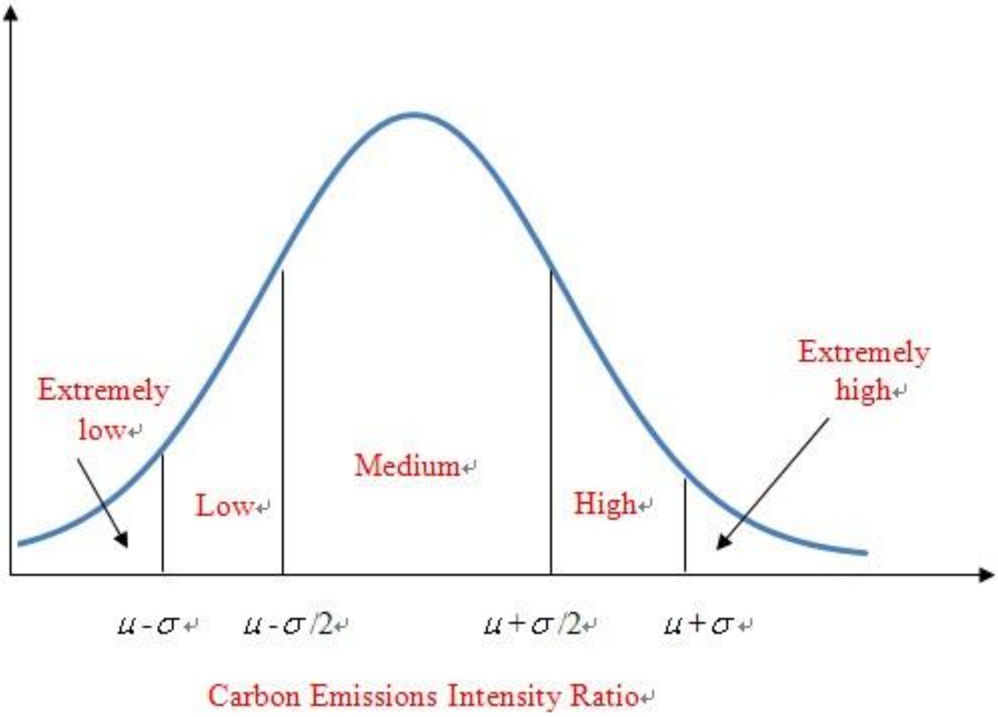

Fig.3.2. Ranges of carbon emissions intensity ratio in terms of the normal distribution

Both μ and σ are calculated based on Equation (3-3), in order to determine the regional boundaries. Thus, the mean of carbon emissions intensity ratio μ can be expressed as follows:

$$\mu = \frac{\sum_{i=1}^{n} CEIR_i}{n} \tag{3-4}$$

where n indicates the sample number of the measured products.

σ is the standard deviation of carbon emissions intensity ratio, which reflects how much variation is from the mean, and can be measured by the following equation.

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(CEIR_i - \mu)^2} \tag{3-5}$$

For example, if a certain product's CEIR approaches the mean, within the standard deviation range $\pm\sigma/2$, it is suggested that the measured product could be labelled as 'medium'.

In order to help customers perceive this dimensionless indicator intuitively, a coloured diagram is developed to present the ratio in a visual way, and thus to improve the effectiveness of carbon labelling scheme. The prototype of the diagram is derived from the concept of 'tolerability of risk', providing a benchmark by which judgments can be made as to whether society should accept the risk, as intolerable, tolerable or acceptable (HSE, 1988). Moreover, HSE has proposed notional boundaries for each region in terms of the risk of death or serious injury to a member of the public (See Fig.3.3). For instance, a risk of 1 in 10^4 per annum to any member of the public is the maximum that should be tolerated from any large industrial plant in any industry. The level of broadly acceptable risk is suggested as 1 in 10^6 per annum (HSE, 1988).

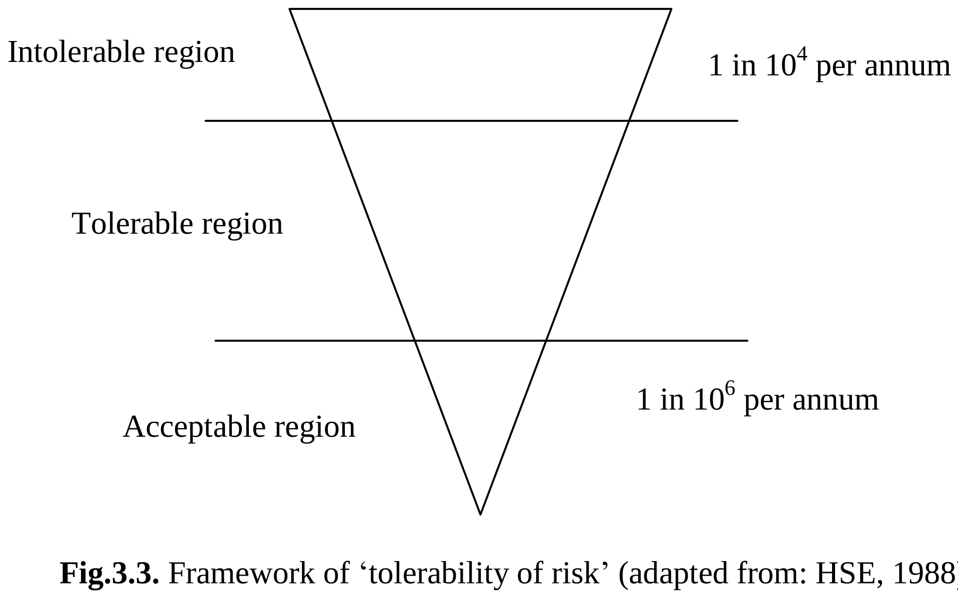

Fig.3.3. Framework of 'tolerability of risk' (adapted from: HSE, 1988)

In this study, it is suggested dividing the inverted triangle into five ranges of carbon emissions intensity ratios. The ranges are highlighted using a background colour that gradually changes from red to green, as the CEIR decreases from extremely high to extremely low (See Fig.3.4).

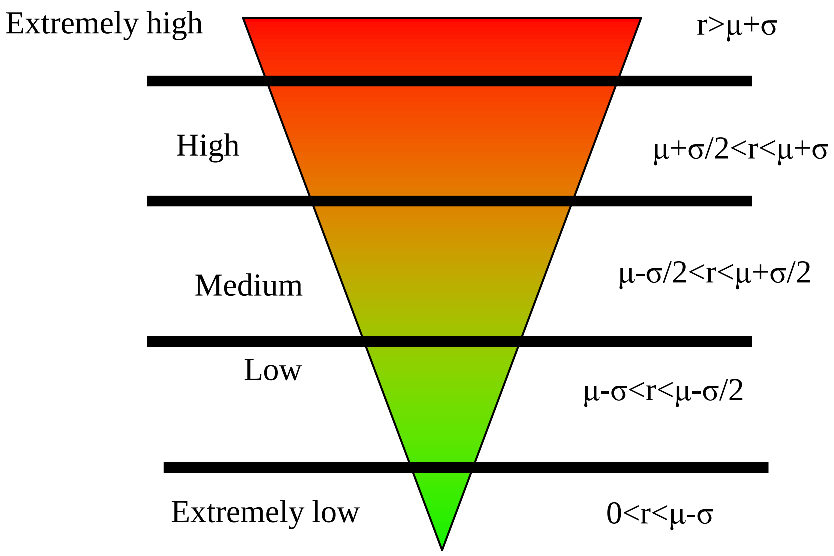

Fig.3.4. Level of carbon emissions intensity ratio

3.3 Case examples

In this section, two case examples are presented to demonstrate the application of the above methodology. The first example uses a wide range of product types to establish a baseline figure for the UK for the purposes of this exercise. The baseline is then applied to calculate CEIR for the included products. The second example demonstrates that the methodology can discriminate between the emissions intensity of similar products, in this case milk with differing fat contents.

3.3.1 Example one: carbon labelling of different product categories

For the purposes of this example we are using the 60 products with carbon emissions data derived from an input-output model developed by Small World Consulting Ltd, in collaboration with Lancaster University (Berners-Lee, 2010). The emissions data were converted to the Carbon Emissions Intensity (CEI) in units of kilograms CO_2 per Pound Sterling (£) of output based on the retail price, Table 3.1. The products can be divided into four categories in terms of their applications, ranging from heavy industrial products, light industrial products, groceries to 'other commercial products'.

As the economic output values of these products are based on 2009 retail prices, the year 2009 is set as the baseline year. Thus, the National Carbon Emissions Intensity (NCEI) for the UK can be calculated as follows:

$$NCEI(2009) = \frac{GHG(2009)}{GDP(2009)} \tag{3-6}$$

where $\mathrm{GHG}(2009)$ is the direct national greenhouse gas emissions of UK at 2009, estimated to be 566,300 million kilograms of carbon dioxide equivalent (DECC, 2011); $\mathrm{GDP}(2009)$ is the national gross domestic product of UK at 2009, given as 2,173,154 million US dollars by the World Bank (2010). As the yearly average currency exchange rate from US dollars to Pounds Sterling is about 0.63 (HM Revenue & Customs, 2011), the GDP value at year 2009 can be transformed into £1,369,087.02 million. Thus, the UK baseline value $\mathrm{NCEI}(2009)$ can be calculated as 0.41 kilograms of carbon emissions per £.

Table 3.1 Carbon footprint intensity of different products
(Reproduced from ‘How bad are bananas: the carbon footprint of everything)

Products	Carbon footprint intensity (Kilograms per ￡ of output value)
Coal	3.56
Oil and gas	0.78
Metal ores	0.99
Stone, clay and minerals	1.06
Processed meat	1.03
Fish	0.85
Processed fish and fruit	0.75
Processed oils and fats	0.75
Dairy products	1.22
Bread and biscuits	0.63
Sugar	1.04
Confectionery	0.35
Alcoholic beverages	0.26
Soft drinks and mineral water	0.51
Tobacco products	0.13
Textile fibers	0.62
Made-up textiles	0.26
Carpets and rugs	0.21
Other textiles	0.58
Knitted products	0.71
Clothing	0.23
Leather products	0.51
Footwear	0.23
Wood and wood products	0.76
Paper and paperboard products	0.71
Petroleum products and coke	0.64
Industrial dyes	1.42
Inorganic chemicals	1.20
Organic chemicals	1.49
Fertilisers	3.05

Table 3.1 (Continued) Carbon footprint intensity of different products
(Reproduced from ‘How bad are bananas: the carbon footprint of everything)

Products	Carbon footprint intensity (Kilograms per ￡ of output value)
Synthetic resins	1.24
Pesticides	1.03
Paints, varnishes, printing ink etc	0.56
Pharmaceuticals	0.27
Soap and toilet preparation	0.26
Man-made fibres	2.07
Rubber products	0.89
Plastic products	0.89

Glass and glass products	0.94
Ceramic products	0.46
Clay products	0.94
Cement, lime and plaster	4.04
Concrete	1.31
Iron and steel	2.63
Non-ferrous metals	1.80
Metal castings	2.86
Metal boilers	0.71
Cutlery tools	0.46
Transmitters for TV and radio	0.44
Receivers for TV and radio	0.23
Motor vehicles	0.72
Furniture	0.52
Jewellery	0.40
Sports products and toys	0.18
Insulated wire and cable	1.07
Domestic appliances	0.44
Agricultural machinery	0.69
Machine tools	0.59
Office machinery and computers	0.36
Electric motors, generators	0.64

Using Equation (3-3), the CEIR of the 60 selected products can now be calculated, as shown in Table 3.2, with μ computed as 2.28, and σ as 1.97, based on Equations (3-4) and (3-5). In this example, therefore, the 'extremely low' region lies between 0 and 0.31, 'low' between 0.31 and 1.29, 'medium' between 1.29 and 3.27, 'high' between 3.27 and 4.25, 'extremely high' above 4.25 (See Fig.3.5).

Table 3.2 Carbon footprint intensity ratio of different products

Products	Carbon footprint intensity ratio	Carbon footprint level
Coal	8.68	Extremely high
Oil and gas	1.90	Medium
Metal ores	2.41	Medium
Stone, clay and minerals	2.59	Medium
Processed meat	2.51	Medium
Fish	2.07	Medium
Processed fish and fruit	1.83	Medium
Processed oils and fats	1.83	Medium
Dairy products	2.98	Medium
Bread and biscuits	1.54	Medium
Sugar	2.54	Medium

Confectionery	0.85	Low
Alcoholic beverages	0.63	Low
Soft drinks and mineral water	1.24	Low
Tobacco products	0.32	Low
Textile fibers	1.51	Medium
Made-up textiles	0.63	Low
Carpets and rugs	0.51	Low
Other textiles	1.41	Medium
Knitted products	1.73	Medium
Clothing	0.56	Low
Leather products	1.24	Low
Footwear	0.56	Low
Wood and wood products	1.85	Medium
Paper and paperboard products	1.73	Medium
Petroleum products and coke	1.56	Medium
Industrial dyes	3.46	High
Inorganic chemicals	2.92	Medium
Organic chemicals	3.63	High
Fertilisers	7.44	Extremely high

Table 3.2 (Continued) Carbon footprint intensity ratio of different products

Products	Carbon footprint intensity ratio	Carbon footprint level
Synthetic resins	3.02	Medium
Pesticides	2.51	Medium
Paints, varnishes, printing ink etc	1.37	Medium
Pharmaceuticals	0.66	Low
Soap and toilet preparation	0.63	Low
Man-made fibres	5.05	Extremely high
Rubber products	2.17	Medium
Plastic products	2.17	Medium
Glass and glass products	2.29	Medium
Ceramic products	1.12	Medium
Clay products	2.29	Medium
Cement, lime and plaster	9.85	Extremely high
Concrete	3.20	Medium
Iron and steel	6.41	Extremely high
Non-ferrous metals	4.39	Extremely high
Metal castings	6.98	Extremely high
Metal boilers	1.73	Medium
Cutlery tools	1.12	Low
Transmitters for TV and radio	1.07	Low
Receivers for TV and radio	0.56	Low
Motor vehicles	1.75	Medium
Furniture	1.27	Low
Jewellery	0.98	Low
Sports products and toys	0.44	Low

Insulated wire and cable	2.61	Medium
Domestic appliances	1.07	Low
Agricultural machinery	1.68	Medium
Machine tools	1.43	Medium
Office machinery and computers	0.88	Low
Electric motors, generators	1.56	Medium

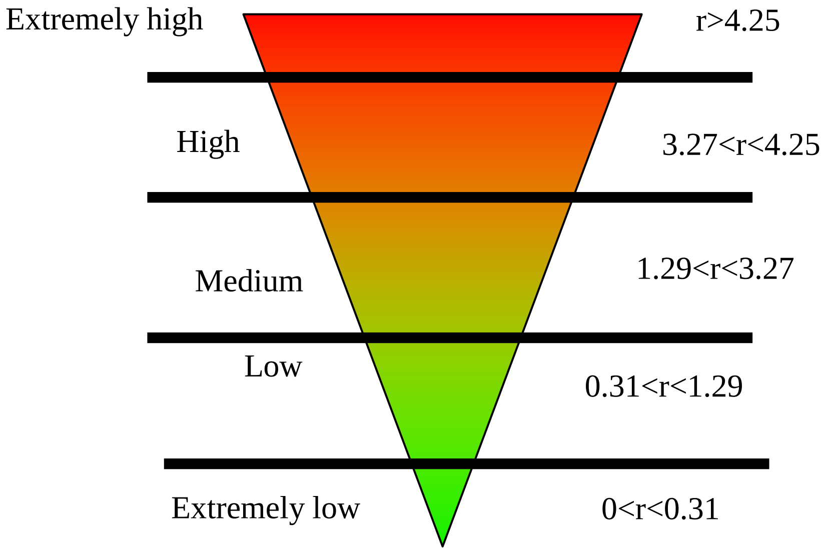

Fig.3.5. Level of CEIR determination based on 60 product categories (Example one)

It is apparent that the CEIR of the selected products is related to the energy embodied in them. Fig.3.6 shows the carbon emissions intensity ratio of 15 heavy industrial products, in which coal, oil and gas, metal ores, coke *etc* are contained. The heavy industrial products (including metal ores and fossil fuels) have CEIR values in the medium to extremely high ranges.

In contrast to the heavy industrial products, the light industrial products are more consumer oriented, instead of via the intermediates used by other industries or manufacturers (Owusu, 2011), in Fig.3.7. However, groceries and some household products have been excluded from the light industrial category in this example, but listed some representative products, such as textiles, fibres *etc*. Man-made fibre shows the highest carbon emissions intensity ratio, whilst other products appear to be at the medium or even at the low values.

The ‘grocery’ category covers not only food and beverages, but also some house-hold products, such as furniture, domestic appliances, cutlery *etc*. Fig.3.8 shows their different CEIRs, most fall into the low range. Compared with heavy industrial products, light industrial, and food products typically have medium to low CEIR values.

Besides, there are five products categorized into ‘other undefined commercial’ products in this case example, including pesticides, paints, fertilizers, industrial dyes and sport products and toys. Their carbon emissions intensity ratios are shown in Fig.3.9. Fertilisers also exhibit an extremely high CEIR value.

Thus, the calculated CEIRs provide a convenient, dimensionless, value by which to compare the emissions intensity of widely different products. Furthermore, these initial values, based on 2009 price figures, would provide an invaluable means of comparing emissions intensity of given products over time. The question remains as to whether the indicator is sufficiently sensitive to enable the separation of similar products on the basis of their emissions intensity, which is a closer simulation of the choices faced by consumers.

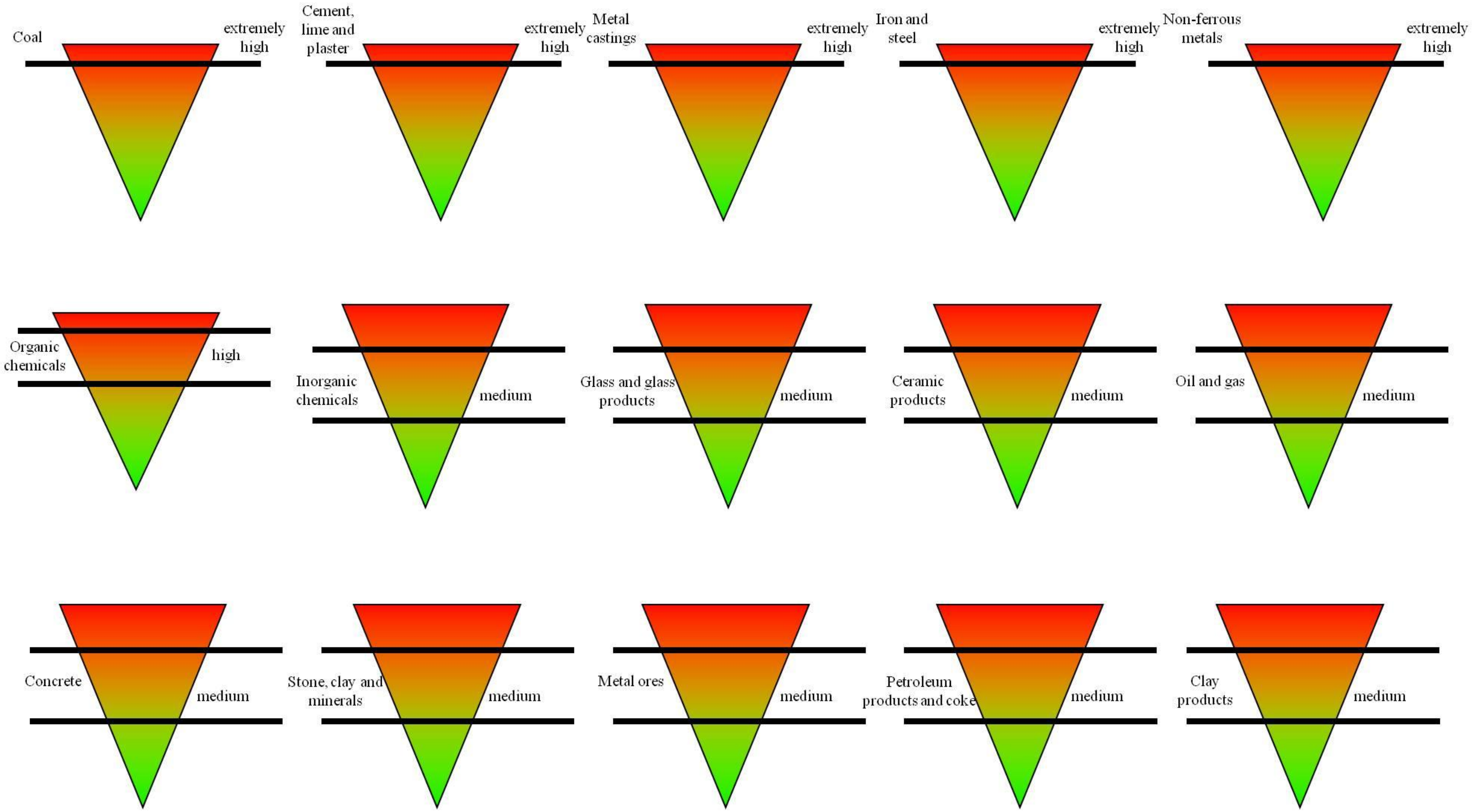

Fig.3.6. Level of CEIR determination based on heavy industrial products (Example one)

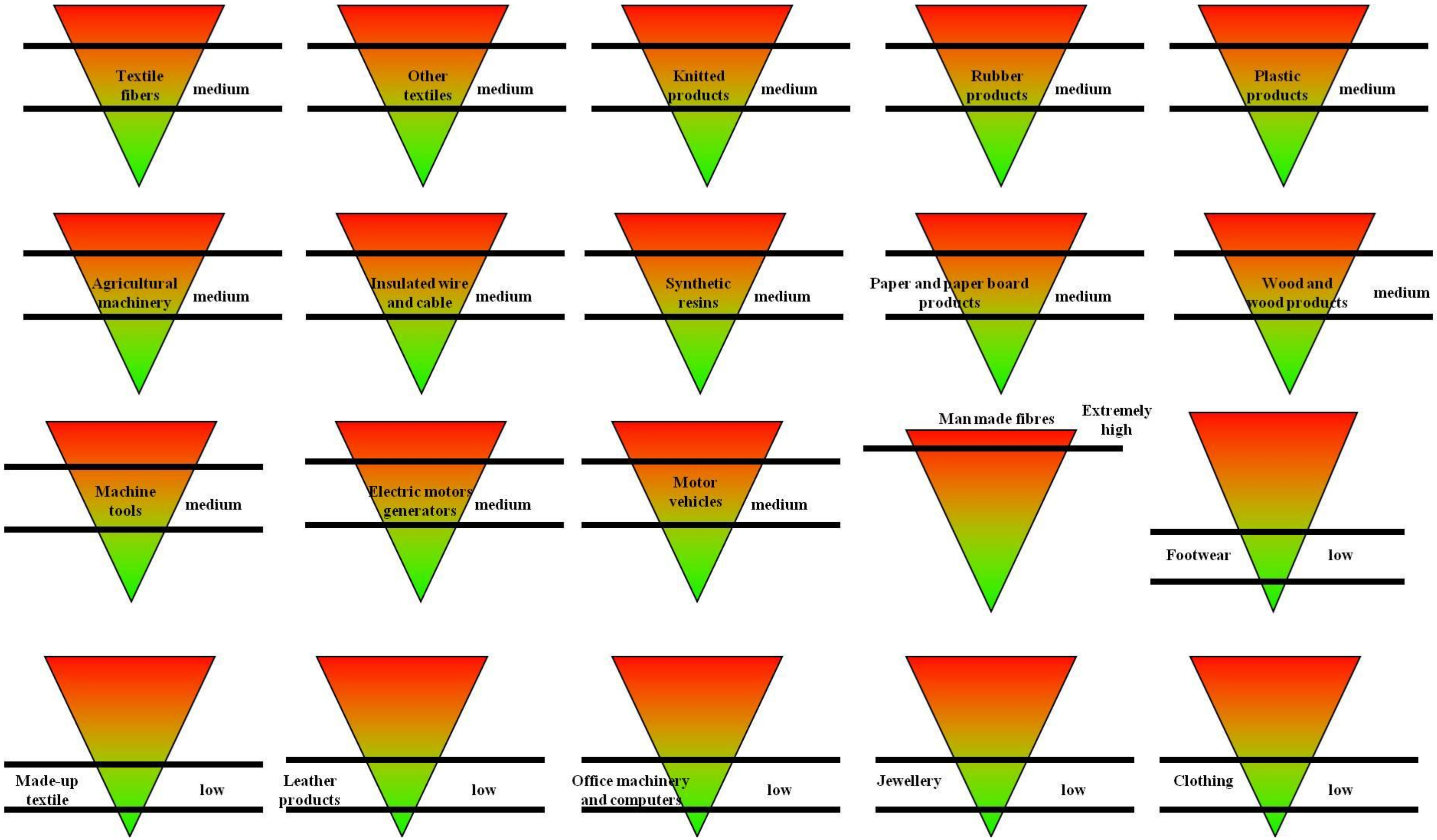

Fig.3.7. Level of CEIR determination based on light industrial products (Example one)

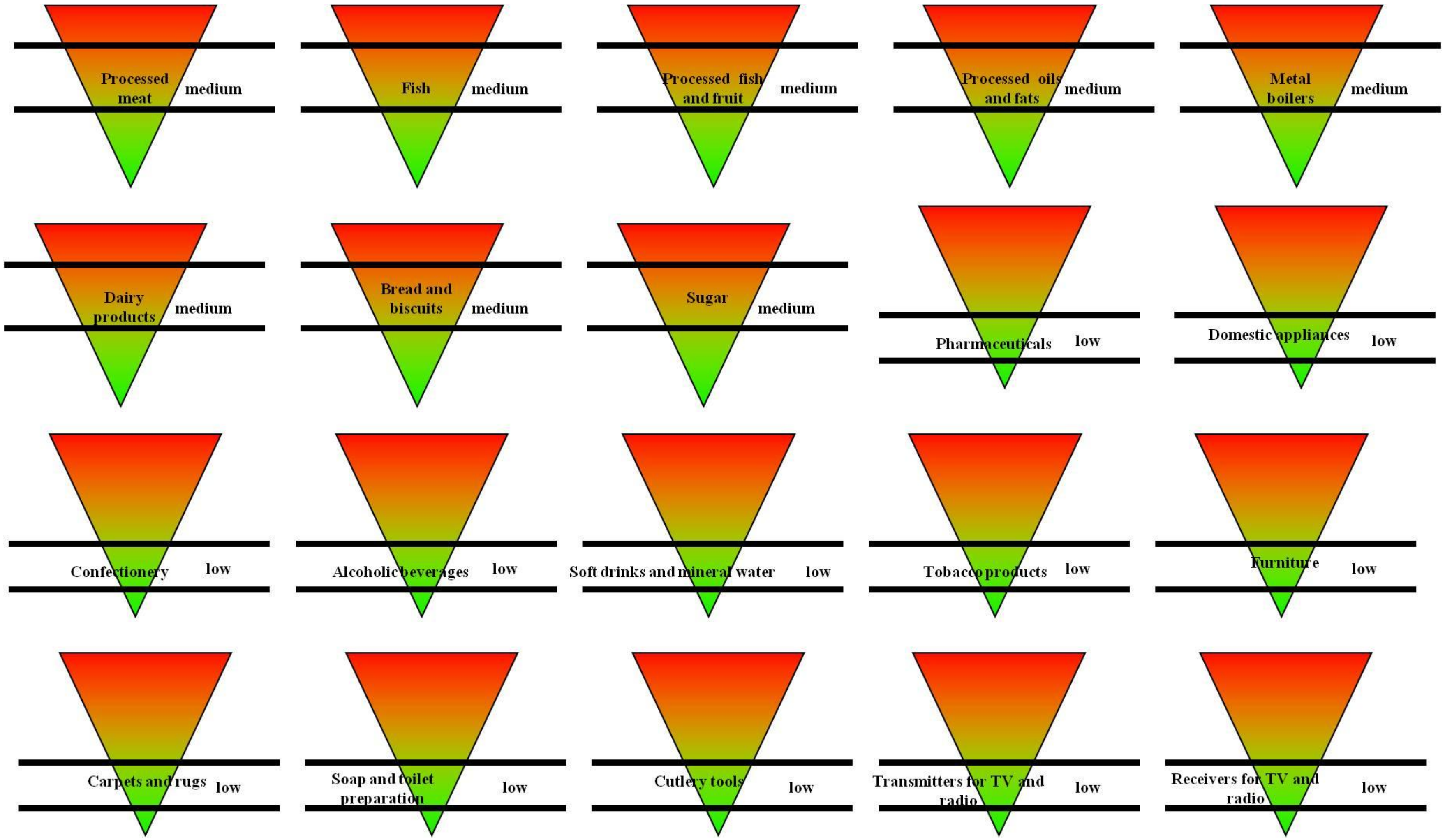

Fig.3.8. Level of CEIR determination based on groceries (Example one)

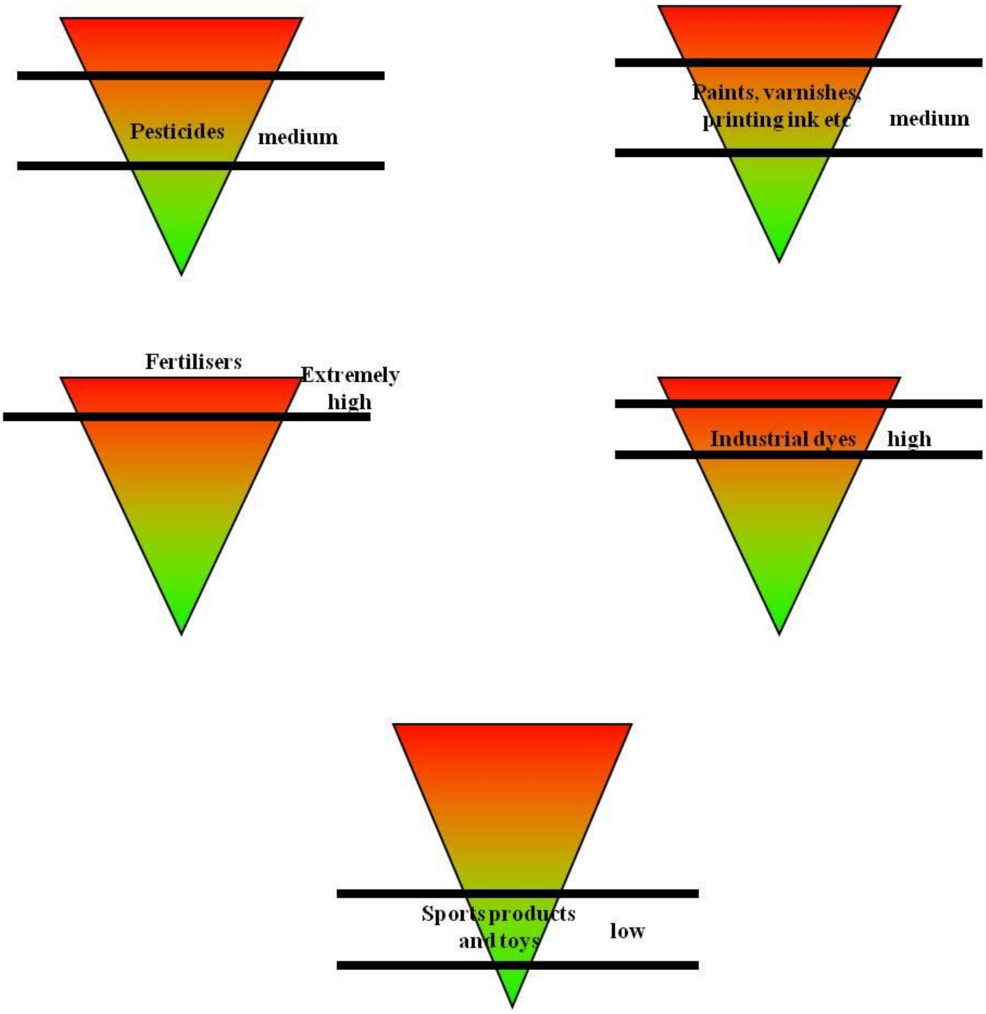

Fig.3.9. Level of CEIR for a selection of products from 'other undefined commercial products' category (Example one)

3.3.2 Example two: carbon labelling of similar products

Example two focuses on a range of similar products, *e.g.* milk, with different fat contents: whole milk (less than 4% fat), semi-skimmed (less than 2% fat) and skimmed milk (less than 0.1% fat). According to an investigation carried out by a leading supermarket in the UK, the present retail price of the above three milk products is the same, 0.49 pounds sterling per pint. Their corresponding carbon footprints, shown in the carbon label, are 0.9 kg CO_2/pint, 0.8 kg CO_2/pint, 0.7 kg CO_2/pint, respectively, Table 3.3. Using the baseline value for NCEI(2009) of 0.41 kilograms per pound sterling

(See example one), the CEI, and its corresponding ratio, can be calculated for the three milk products from the equations (3-1) and (3-3), Table 3.4.

Table 3.3 Carbon emissions and retail price of three investigated milk products

Milk products	Carbon emissions per pint (Kg)	Retail price (one pint milk) (Pound sterling)
Whole milk (<4% fat)	0.9	0.49
Semi-skimmed milk (<2% fat)	0.8	0.49
Skimmed milk (<0.1% fat)	0.7	0.49

Table 3.4 Carbon emissions intensity and its ratio of three investigated milk products

Milk products	Carbon emissions intensity (Kg per Pound)	Carbon emissions intensity ratio
Whole milk (<4% fat)	1.84	4.49
Semi-skimmed milk (<2% fat)	1.63	3.98
Skimmed milk (<0.1% fat)	1.43	3.49

Since milk is a dairy product, one of the 60 selected products presented in the example one, it can be deemed to be included in the normal distribution of carbon labelled products divided into the various regions. Hence, the levels of carbon emissions intensity ratio, defined in Fig.3.5 are still relevant to the three milk products. Milk is a high carbon product (Berners-Lee, 2010): both semi-skimmed and skimmed milk show high CEIRs, whilst whole milk's CEIR is extremely high (See Fig.3.10).

The CEIR, therefore, is capable of distinguishing between similar products, even, as in this case, variants of the same product. Notably, dairy products overall had a medium CEIR (See Table 3.2). The reason can be explained as the difference between the individual and entire samples, *i.e.* dairy products include varieties, such as milk, milk powder, butter, cheese, cream, yogurt *etc*. On the one hand, the carbon emissions intensity ratio for certain variety can be low, medium or high, *e.g.* the milk investigated in this example shows at the high or extremely high level. On the other hand, the CEIR for the entirety as dairy products still remains at a comparatively stable level, *i.e.* medium. An emissions-conscious consumer, therefore, would be able to use the information provided by CEIR labelling to adjust their consumption habits in such a way as to obtain the nutritional benefits of dairy products whilst reducing their personal carbon footprint.

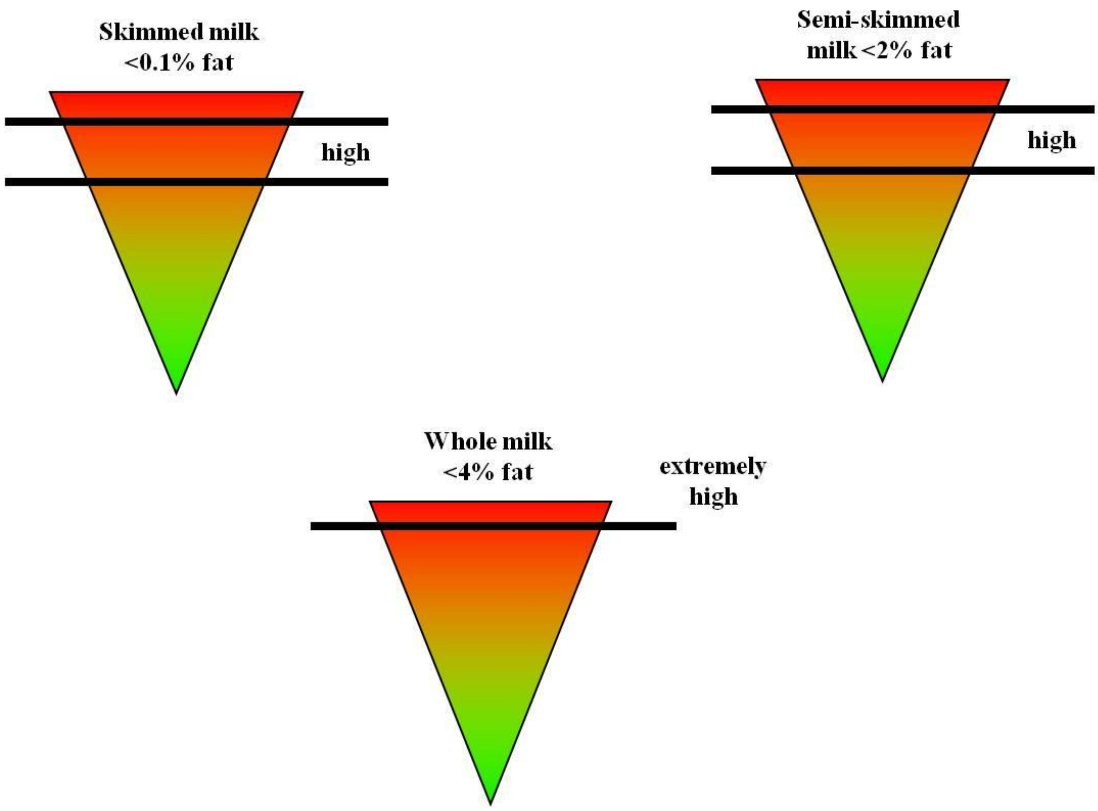

Fig.3.10. Level of CEIR determination based on similar milk products (Example two)

3.4 Discussion

No carbon emissions indicator can be more accurate or precise than the inputs from which it is derived. In this instance the inputs can be divided between those relating to the measurement of carbon emissions, and those relating to the financial data. The most critical input for any carbon emissions indicator is the LCA emissions data. As discussed, the complexities of LCA and difficulties in obtaining the required data limit the precision of calculated values. In addition, there may be biases in the types of products for which values have been calculated, which would influence the CEI. Additionally, the national emissions data used to calculate the baseline value are likely to vary significantly in methodology of collection and presentation between different countries, which will hinder international comparison of CEIR.

For financially based emissions intensities, a significant problem is posed by fluctuations in retail prices. The proposed methodology corrects for this, but there are uncertainties in the process, with a number of different methods available for providing a constant value to fluctuating prices. The methodology needs to be tested for sensitivity to calculations of inflation and the assumptions made on short term price fluctuations. (*e.g.,* is average recommended retail price for the year used, or are sale prices taken into consideration or price discrepancies between different outlets).

One potential innovation to LCA would be to combine the existing life cycle assessment approach with other methods, such as Organisation Product based Life Cycle Assessment (OP-LCA), Input–Output Analysis based Life Cycle Assessment (IO-LCA). This would allow better comparability by using the financial accounts as a unique functional unit and including all relevant products and processes (Berners-Lee, 2010; Carballo-Penela and Doménech, 2010). In this case, the first step of the proposed methodology (division by inflation corrected retail price) for carbon labelling could be omitted. However, the financial values used in any hybrid LCA approach would need to be corrected for variations over time.

3.5 Summary

This Chapter presents an improved carbon labelling scheme to help consumers not only to better understand the concept of carbon footprint, but also to appreciate the significance of a product's carbon footprint in a more visual way. This approach starts by normalizing carbon emissions data on a common scale of 'Carbon Emissions Intensity', and a new indicator 'Carbon Emissions Intensity Ratio' is generated based upon its ratio to the annual national greenhouse gas emission per gross domestic product. Five ranges (extremely low, low, medium, high and extremely high) are used to represent the level of carbon emission intensity ratio by a simple diagram with colour gradation. Two case examples are presented, in which the Carbon Emissions Intensity Ratio of various selected products, both distinct and related, are calculated and compared.

As it is evident that consumers drive the open market, and their preference may be influenced by the carbon footprint label of products, to demand better, safer and sustainable products for consumption, as well as to promote cleaner production, which should be also attached more importance by manufacturers and government. Although the public demand is the principal driver for industrial innovation and adjustment, there might be different interests and dilemmas within the stakeholders, *i.e.* manufacturers and government.

Thus, the following chapters first introduce the basis of game theory, and then illustrate its application to cleaner production, supply chain respectively to identify the appropriate strategy for manufacturers and government whilst optimising sustainability or the three dimensions (economic, social and environment).

Chapter 4: Game Theory Basis for Decision-Making

4.1 Introduction

In this Chapter, the fundamentals of game theory are introduced, which will also be used for further analysis within different game scenarios. It is considered that game theory for decision-making can be similar to the mathematical modelling process (Shier and Wallenius, 2000), as a game problem is ultimately resolved by a model. Therefore, the mathematical modelling process can be deemed as a general framework for game theory application, but one which needs to be adjusted according to the specific game circumstance.

The specific process of game theory for decision making is described in Figure 4.1, based upon the above prototype. Within the loop cycle of the decision-making process, there are four key stages which are: (a) game situation analysis, (b) game modelling, (c) game result interpretation, and (d) decision-making for players in turn. Game situation is usually derived from a realistic issue, where conflicts or different interests are involved (Geckil and Anderson, 2010). In this premise, essential factors that formulate a game, as "players", "payoffs" and "strategies" should be analyzed. The decision-maker with different interests can be seen as a 'player' in a game. A payoff is what a player may possibly gain in the game situation, depending upon the strategic actions of all the players. Strategy can be set as the rule of a game, to describe how a player could play (Romp, 1997). Moreover, such questions as "how many players in the game", "how many strategies for each player", "what is the possible strategic action for each player", "what is the possible payoff for each player" *etc*, should be considered at this stage. Based upon the game situation analysis, the practical problem can be quantified or semi-quantified in the corresponding models in terms of different game forms, *e.g.*

normal or extensive form, or various game scenarios, *e.g.* static, dynamic, evolutionary game theory. The solution of a game is to determine what strategic action each player will select, and the result can be interpreted as an equilibrium (agreement) by considering the interaction between the players to maximize the individual or group interests (Romp, 1997). The agreement could be a long term or short term equilibrium to aid decision-making for the players involved. Once the equilibrium has been broken, a new game situation will be generated to find out the alternative strategic action for each player.

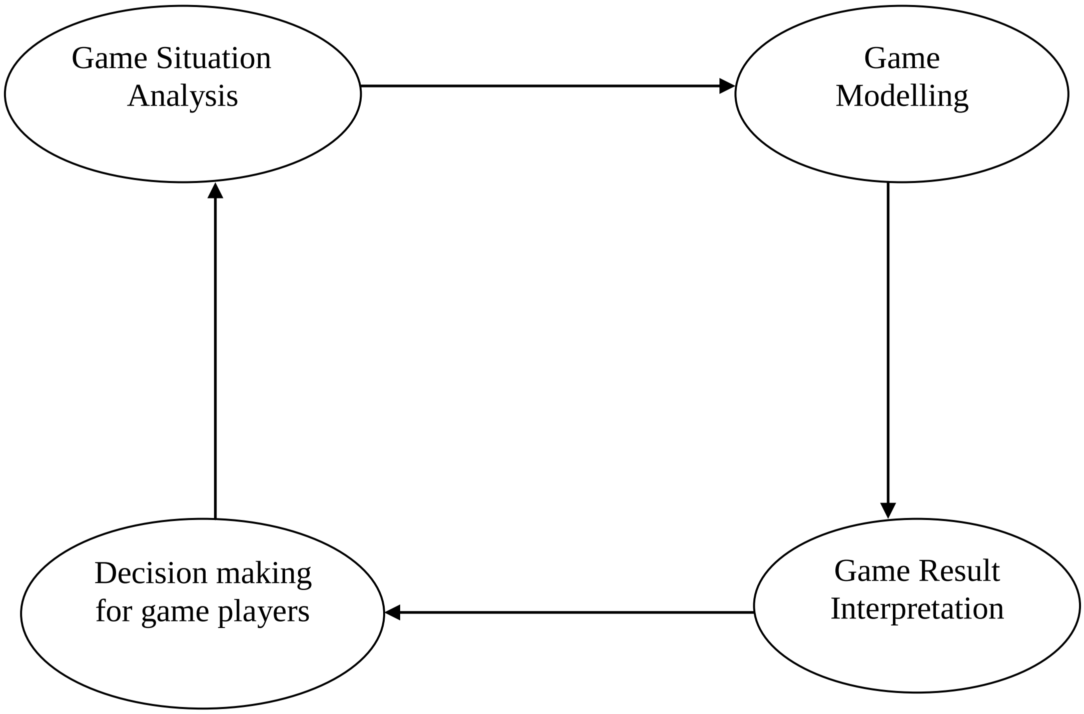

Fig.4.1. Decision making process by using game theory

4.2 Prisoner's dilemma

In this Section, a well-known game example called "The Prisoner's Dilemma" (Davis, 1983; Luce and Raiffa, 1989; Straffin, 1993) is introduced more specifically to present the above decision making process. The significance of Prisoner's Dilemma is that considerable social phenomena or issues which are found in our life can be abstracted and explained as the prisoner's choices in a way (Straffin, 1993). Moreover, this game situation can be seen as a prototype to develop the game scenarios in this study, to discuss the potential strategic selection between manufacturers and government in the Chapter 5 and 6.

For instance, the environmentally friendly products are advocated as an assumption in our study, which may lead to further competition within those manufacturers that produce the same type of products. It is assumed that two manufacturers will not only engage in a cost reduction war, but will also become involved in a product quality improvement, *e.g.* reducing the inherent risk and carbon footprint associated with products. If both industries cut the economic cost of production, and lay stress on environmental protection such as reducing the risk to public health, and carbon footprint of the products, they may have the opportunity to explore a new market share. Otherwise, if both industries do not put emphasis on the environmental consideration, but just maximize their own economic interests, their long term sales profit may decrease gradually. If one industry adopts new and clean technology for cleaner production to save the cost and energy of manufacturing on the one hand, provides environmental friendly product on the other hand, and another industry still insists on their inherent action for production without taking any environmental considerations into account, the former industry apparently may have advantages to attract more customers to buy their products, thus increasing profits and seeking additional financial support as subsidy from government. However, the latter one may have less economic risk resulting from technical innovation.

Now return to the "prisoner's dilemma", which is a classical game in the field of game theory. It is originally generated by Albert W. Thucker (Romp, 1997), and has been gradually developed by many game researchers. There are two players in the game, who are detained in separate rooms as being the two suspect criminals in a particular case. The policeman is very experienced, but without adequate evidence to sentence them in the trial process. Therefore, he tries to give each player two alternative choices, to confess what they have done, or not to confess. Therefore, the dilemma faced by the two prisoners is to choose whether to confess or not. The potential combinations of the choices that they would make are presented as follows.

If both of them choose not to confess, due to the absence of direct evidence of their guilt, other accusations as misdemeanours are adjudicated so that they could be imposed in a lighter punishment, *i.e.* both of them are sentenced to one year in jail. If they both choose to confess to the policemen, they will be found guilty but will be sentenced to less severe punishment. Thus both of them will be sentenced to six years in jail. If one of them determines to confess and another one rejects to confess, the confessor will receive a reduced penalty as a reward, whilst his partner will be punished heavily. It is assumed the confessor can be exempt from jail, but his partner who denied confessing, will be sentenced for ten years. Here, the penalties can be arbitrary, and only seen to be illustrative in this example. According to the above set of potential strategic actions, this problem can be described in a matrix below, shown in Table 4.1.

Table 4.1 Payoffs matrix of the "Prisoner's Dilemma"

		Prisoner 2	
		Not Confess	Confess
Prisoner 1	Not Confess	(-1, -1)	(-10, 0)
	Confess	(0, -10)	(-6, -6)

The “prisoner’s dilemma” belongs to the “strategic form game”. If a game is defined as the strategic form game, the game should contain the following three important factors, which are “the list of players”, “the set of strategies available to each player”, “the payoffs associated with any strategy combination (one strategy per player)” , respectively (Dutta, 1999). Payoffs in game theory can be described as the real numbers “positive or negative” given for different situations. And moreover, these numbers are generally derived by the outcomes in the game theory. In some cases, the payoff is using a logic unit instead of the monetary value. For instance, if the outcome can be interpreted as win, lose and draw, accordingly there are values “1”, “-1”, “0” to stand for these three situations separately (Rapoport, 1999; Thomas, 2003). Within the “strategic form game”, the simplest form is the “two person game”, which describes that two players are in the game situation and each of them has two available strategies for further selection. Moreover, the two person game can be divided into two categories, within which one is called “two-person zero-sum game” and another one is called “two-person non zero-sum game” (Rapoport, 1999).

A “two-person zero-sum” game is a game that the player’s payoffs add up to be zero no matter what strategy they would use (Kelly, 2003; Thomas, 2003). In such a game situation, the competition is very strict, that one player will win and the other will lose. The “two-person zero-sum” game is applicable for daily life, but in some real circumstance, the payoffs cannot equal to zero as the game is unfair to some extent. However, it is found that the sum could be a constant as the result of the extreme competitive game. In order for simplicity, the term “zero-sum” can be interpreted as “constant sum” in a way which means “players have diametrically opposed the interests” (Davis, 1983).

The “Prisoner’s dilemma” is a typical “two person non-zero-sum game” by the reason that the total payoff is twelve years if both players decide to confess and two year if they do not confess. Thus, the payoffs of the players cannot be summed as zero in this game and thus the term “non-zero-sum” is used. In contrast with the two person zero-sum game, it is a non-strictly competitive game in which the players are not “completely antagonistic to one another” (Luce and Raiffa, 1989; Thomas, 2003). In the non zero-sum game, the outcome could be beneficial and acceptable to all the players involved, as no one will win everything but everyone will get something instead. To some extent, this can be understood as a “win-win” situation which is different from the zero-sum game as strict “win-lose” situation. Many conflicts related to economic, political and military interests can be transformed into a non zero-sum game situation. For example, the game scenarios of medical products development could be based on the non zero-sum game with various degrees of cooperation and competition (Luce and Raiffa, 1989; Whitmore, 2003). The basic form of non zero-sum game can be also applied in this study, in order to build different game scenarios in the context of cleaner production and green supply chain network, which is discussed in the Chapter 5 and 6.

4.3 Nash equilibrium

The solution of “two person non zero-sum game”, *e.g.* “Prisoners’ Dilemma”, is determined by finding out the possible “Nash Equilibrium”. Assume that a game makes the unique predication from the possible strategic actions that each player may choose. Moreover, the predicted strategy should be a best response compared with the strategies chosen by all the other players. Therefore, such prediction is called as “Nash Equilibrium”, by which the mathematical definition is expressed as followed (Gibbons, 1992).

Assume that there are n players in the game $G=\{S_1,...,S_n;u_1,...,u_n\}$, the strategies $(s_1^*,...,s_n^*)$ are a Nash equilibrium if, for each player i, s_i^* is player i's best response to the strategies specified for the $n-1$ other players, $(s_1^*,...,s_{i-1}^*,s_{i+1}^*,...,s_n^*)$:

$$u_i(s_1^*,...,s_{i-1}^*,s_{i+1}^*,...,s_n^*) \geq u_i(s_1^*,...,s_{i-1}^*,s_i,s_{i+1}^*,...,s_n^*)$$

For every feasible strategy s_i in S_i; that is s_i^* solves

$$\max_{s_i \in S_i} u_i(s_i^*,...,s_{i-1}^*,s_i,s_{i+1}^*,...,s_n^*)$$

Generally speaking, there are two stages to find out Nash equilibrium for any game. First of all, the optimum strategic action for each player should be determined in turn. This is done for every combination of strategies by the other players. Consequently, a pair of Nash Equilibria can be identified since all the players choose their optimal strategies simultaneously. This method is only used to solve the game with pure strategies. A pure strategy can be defined as "a restricted mixed strategy with a probability of one given to the chosen strategy, while zero to the others" (Romp, 1997). Accordingly, pure strategy equilibrium is a specific strategy that each player chooses.

However, a mixed-strategy equilibrium is that at least one player involved in the game randomizes over some or all of the pure strategies. This means a probabilistic distribution should be placed by the strategies selection. Therefore, it is supposed that pure strategy equilibrium should be a special case of mixed-strategy equilibrium. In order to present how to find out the Nash Equilibrium for the above game example "Prisoners' dilemma", it is considered using the method of "Elimination of dominated strategies" (Romp, 1997; Gintis, 2009) and "Swastika" method (Thomas, 2003), respectively. Moreover, either of these two methods can be applied further to solve the game models detailed in Chapter 5 and 6.

4.3.1 Elimination of dominated strategy

'Dominant strategy' is defined as the optimal strategy for a player, no matter what the other player chooses (Geckil and Anderson, 2010). However, a strategy is deemed as dominated, if other strategies always bring about the improved payoffs no matter what the players in the game choose (Romp, 1997). The "Prisoners' Dilemma" is solved by the elimination of the dominated strategy, to find out the maxmin-maxmin strategic pair. In applying this method, each player should be examined in turn and all those strategies that are strictly dominated should be eliminated. This process may rule out all but one strategy left for each player. Therefore, this method provides a unique solution for the game. Table 4.2 shows the different payoffs between two prisoners while taking the different strategic actions, "Confess" or "not confess".

Table 4.2 Prisoners' dilemma in normal form

		Prisoner 2	
Prisoner 1		Confess	Not confess
	Confess	-6, -6	0, -10
	Not confess	-10, 0	-1, -1

At first, identify the optimum strategy for Prisoner 1, dependent upon what the prisoner 2 may choose. Suppose Prisoner 1 predicts that Prisoner 2 may choose "Confess", the best strategy for Prisoner 1 is also to "confess" derived from the matrix $\begin{bmatrix} -6 \\ -10 \end{bmatrix}$, since -6 is better than -10. As the payoffs are used to represent the duration of imprisonment, the numerical values should be as least as possible. Thus, it is shown in Table 4.3 by underlining and overstriking the first payoff element "-6" when the Prisoner 2 chooses "confess".

Table 4.3 Prisoner 1's optimal choice while Prisoner 2 selecting "confess"

Prisoner 1		Prisoner 2	
		Confess	Not confess
	Confess	**-6**, -6	0, -10
	Not confess	-10, 0	-1, -1

If the Prisoner 1 predicts that Prisoner 2 may choose the action "Not confess", the best strategy for Prisoner 1 is also to "confess" derived from the matrix $\begin{bmatrix} 0 \\ -1 \end{bmatrix}$, as 0 is better than -1. In this case, Prisoner 1 could be exempt from jail as all the punishment will be undertaken by Prisoner 2. Thus, it is considered to underline and overstrike "0" in Table 4.4.

Table 4.4 Prisoner 1's optimal choice while Prisoner 2 selecting "Not confess"

Prisoner 1		Prisoner 2	
		Confess	Not confess
	Confess	-6, -6	**0**, -10
	Not confess	-10, 0	-1, -1

Similarly, determine the optimal strategy for Prisoner 2, by forecasting the possible action choice of Prisoner 1 (taking the array into account). Suppose that Prisoner 1 may select "confess", and the best strategy for Prisoner 2 is also to "confess" derived from the matrix $\begin{bmatrix} -6, -10 \end{bmatrix}$, as -6 is also better than -10. Thus, it is considered to underline and overstrike "-6" in Table 4.5.

Table 4.5 Prisoner 2's optimal choice while Prisoner1 selecting "confess"

Prisoner 1		Prisoner 2	
		Confess	Not confess
	Confess	-6, -**6**	0, -10
	Not confess	-10, 0	-1, -1

When Prisoner 1 may select “not confess”, Prisoner 2 would better to choose “confess”. From the matrix $[0,-1]$, he could be exempted from the jail. Accordingly, the selected payoff element is shown in Table 4.6.

Table 4.6 Prisoner2’s optimal choice while Prisoner1 selecting “Not confess”

		Prisoner 2	
Prisoner 1		Confess	Not confess
	Confess	-6, -6	0, -10
	Not confess	-10, **0**	-1, -1

In summary, all the selected optimal payoffs are shown in Table 4.7, with being underlined and over-striked. If the payoffs in the same box are underlined and over-striked, it is deem that the corresponding strategic pair is the dominant strategy in the game.

Table 4.7 Prisoner2’s optimal choice while Prisoner1 selecting “Not confess”

		Prisoner 2	
Prisoner 1		Confess	Not confess
	Confess	**-6**, **-6**	**0**, -10
	Not confess	-10, **0**	-1, -1

In the prisoners' dilemma, it is clear that there is only one box where both payoffs have been underlined and over-striked, which corresponds to both prisoners confessing. Thus, the Nash equilibrium is unique in this game.

However, this result seems to be a not ‘satisfactory’ solution as it leads the payoffs pair (-6, -6), which is worse than (-1, -1), if both players choose “confess”. This is because the individualism could be superior to the group rationality in the context of Non-cooperative game theory. It assumes that the individual action is determined to only act in self-interest (Romp, 1997; Thomas, 2003). In contrast, the players could enter into a binding and enforceable agreement in the field of the cooperative game, so that the two prisoners are better to choose "not confess". As individuals are assumed to work together in a voluntary instead of a compulsory way, the non-cooperative game theory research is more prevalent in the economic activities (Romp, 1997). Thus, the following studies on application of game theory to cleaner production and supply chain are all based upon this premise, and affiliated with the non-cooperative game.

4.3.2 Swastika method

The Swastika method is a graphical approach for determining all the Nash equilibrium pairs for a "Two Person Non-cooperative" game. The name of this method is deriving from the final diagram which looks like a "Swastika" (Thomas, 2003).

Nash Theorem (1950): In the n-player normal-form game $G = \{S_1, \ldots S_n; u_1, \ldots u_n\}$, if n is finite and S_i is finite for every i then there exists at least one Nash equilibrium, and possibly involving mixed strategies.

In the premise of "Nash Theorem", any two-person game (zero-sum or non zero-sum) with a finite number of pure strategies has at least one equilibrium pair. Suppose a pair of strategies $x^* \in X$, $y^* \in Y$ is an equilibrium pair for a non zero-sum game, the necessary and sufficient conditions should be satisfied for any $x \in X, y \in Y$:

$$e_1(x^*, y^*) \geq e_1(x, y^*) \tag{4-1}$$

$$e_2(x^*, y^*) \geq e_2(x^*, y) \tag{4-2}$$

The "Prisoner's dilemma" game still uses "Nash Theorem" to find out all the equilibrium pairs. In order for computation, the normal form of "Prisoner's dilemma" (See Table 4.2) can be expressed in a matrix form below.

$$\begin{array}{cc} & \begin{array}{cc} \text{II}_1 & \text{II}_2 \end{array} \\ \begin{array}{c} \text{I}_1 \\ \\ \text{I}_2 \end{array} & \begin{bmatrix} (-6,-6) & (0,-10) \\ \\ (-10,0) & (-1,-1) \end{bmatrix} \end{array}$$

In this example, suppose the mix-strategies for prisoner I and II are $(x, 1-x)$, and $(y, 1-y)$, respectively. According to the inequality (4-1), for a particular y which is part of an equilibrium pair, x can be found to maximize $e_1(x, y)$. Thus, the x must be its partner in it. If $x = 1$ which means no matter what y is, prisoner 1 should choose "confess" as the pure strategy. Thus, the expected payoffs of prisoner 1 should be less than or equal to the payoffs once "confess" has been selected. The expression can be obtained as follows:

$$e_1(x, y) \geq e_1(1, y) \tag{4-3}$$

where $e_1(x, y)$ can be expressed as followed:

$$e_1(x, y) = -6xy + 0x(1-y) - 10(1-x)y - 1(1-x)(1-y) = 3y(x-3) + (x-1) \tag{4-4}$$

Let $x = 1$, and substitute the numerical value into equation (4-4) and the inequality (4-3), thus the indeterminate form expressions can be transformed as follows:

$$3y(x-3)+(x-1)\geq -6y \tag{4-5}$$

Through further mathematical simplification as the merger of similar items for the above expressions, the final expressions can be obtained as below:

$$3(x-1)(y+\frac{1}{3})\geq 0 \tag{4-6}$$

Followed by the constraint conditions of x and y, the following linear simultaneous inequalities (4-7) can be solved if and only if $x=1$.

$$\begin{cases} 3(x-1)(y+\frac{1}{3})\geq 0 \\ 0\leq x\leq 1 \\ 0\leq y\leq 1 \end{cases} \tag{4-7}$$

Similarly, any fixed x, y could be found to maximise $e_2(x,y)$. If x is part of an equilibrium pair, y should be its partner. If $y=1$ which means no matter what x is, prisoner 2 would choose "confess" as the pure strategy. Thus, the expected payoff of prisoner 2 should be less than or equal to the payoff once "confess" being selected. Thus, the expression should satisfy the following:

$$e_2(x,y)\geq e_2(x,1) \tag{4-8}$$

where $e_2(x,y)$ can be expressed as followed:

$$e_2(x,y)=-6xy-10x(1-y)+0(1-x)y-1(1-x)(1-y)=3x(y-3)+(y-1) \tag{4-9}$$

Let $y=1$ and substitute the value into equation (4-9) and the inequality (4-8), thus the indeterminate form expressions can be derived as follows:

$$3x(3-y)+(1-y)\geq -6x \qquad (4\text{-}10)$$

The simplified expressions can be obtained as followed, by means of the merger of similar items from the above inequality (4-10).

$$3(y-1)(x+\frac{1}{3})\geq 0 \qquad (4\text{-}11)$$

Combining the constraint conditions of x and y with the inequality (4-11), the following linear simultaneous inequalities (4-12) can be solved if and only if $y=1$.

$$\begin{cases} 3(y-1)(x+\frac{1}{3})\geq 0 \\ 0\leq x\leq 1 \\ 0\leq y\leq 1 \end{cases} \qquad (4\text{-}12)$$

Thus, $(x,y)=(1,1)$ should be the unique Nash equilibrium solved by the inequalities (4-7) and (4-12), where the corresponding payoffs are $(-6,-6)$ that means each prisoner should be sentenced to 6 years in jail. The equilibrium pair is shown in Fig.4.2. Moreover, the Nash equilibrium reflects the probability that both players determine to confess is one, whilst the probability of not confessing is zero.

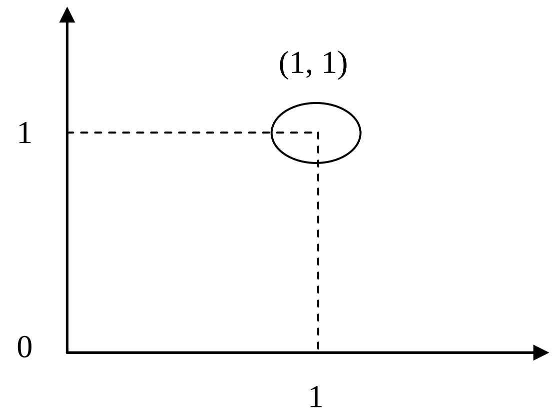

Fig.4.2. Swastika method for equilibrium pair

As the "Prisoner's dilemma" is a pure-strategic game, it shows strictly dominant strategy. Both of the two methods show that the optimum strategy is both to confess in the context of "Non-cooperative Game". However, the "prisoner's dilemma" is used to express the simplest situation of a game, the real game between manufacturers and government is more complex, which is presented in the following Chapter 5 and 6.

4.4 Summary

This Chapter provides the fundamentals of game theory, which are used for further game theoretical analysis and simulation. The starting point is to introduce the general process of decision-making by using game theory, which can be divided into four stages with a circular routine, as game situation analysis, game modelling, game result interpretation and decision-making for game players. Moreover, a classical game that the "Prisoners' dilemma" is introduced as an example to illustrate how to use game theory for decision making. In particular, any game to be built further in this study may consider the "Prisoner's Dilemma" as an analogy. The game problem can be generally solved by means of the "Nash Equilibrium" calculation, to find out the predicted strategic action for all the players involved. Thus, two approaches as "elimination of dominated strategy" and "Swastika method" are presented to find out the potential Nash equilibrium by using the "Prisoner's dilemma" example. Furthermore, these approaches will be employed to solve the game developed in this research. Subsequently, Chapter 5 describes a game in the field of cleaner production, and discusses the possible strategic options of the involved players: government and manufacturers, by showing how game theory could be applied to better understand their dilemmas.

Chapter 5: Game Theory Application to Cleaner Production

5.1 Introduction

In the context of sustainable development, all materials can be deemed as 'hazardous' in certain situations because of their inherent risk, such as the various stages of the product lifecycle, *i.e.* production, delivery, use and final disposal. From the standpoint of 'Hierarchy of Waste Management', cleaner production is suggested as an effective way to prevent environmental contamination and thus to reduce the environmental risk and carbon footprint especially in the final disposal. Cleaner production has been defined as "*the continuous application of an integrated, preventive strategy to processes, products and services to increase efficiency and reduce risks to humans and the environment*" (UNEP, 2006). This can be applied to any point in a product's life cycle in order to mitigate the adverse impact on the environment and human health by decreasing the amount or toxicity of raw materials used in the manufacture or packaging of a product; redesigning products in order to increase their lifecycle, reusability and reparability; reforming the quality of products by which the residual toxicity and waste once products entering the post-consuming stage should have been minimized; changing the patterns of raw materials demand and consumption that reduce the amount and toxicity of waste generated, *etc*. (Tchobanoglous, 2002, Allen and Rosselot; 2004).

Whilst such strategies can bring economic as well as environmental benefits, for example via energy savings or reductions in the amount of raw materials purchases, or reduction in the costs of waste disposal by reducing the amount and/or toxicity of waste for disposal (Smith, Hargroves and Desa, 2010), there is little dispute that the state has a role in setting a policy context conducive to cleaner production. For instance, the Chinese government has a stated policy of promoting cleaner production as a route to sustainable development, in which subsidies including tax breaks, equipment upgrading *etc*., are offered to enterprises for the implementation of cleaner production (China NDRC, 2008, Dong *et al.*, 2010). As Smith, Hargroves and Desa (2010) also emphasise, a range of policy interventions is needed to promote sustainable production.

However, the policies will have to confront uncertainties during the implementation of cleaner production, due to the conflict of interests between the relevant stakeholders, especially between the government and manufacturers (Dong *et al.*, 2010). Furthermore, whilst environmental policies are essential to achieve sustainable development, they may not be sufficient. Even in the context of the EU, which has put environmental regulations firmly on the policy agenda since the 1970s, many manufacturers still primarily focus on the profit which is the original bottom line for business (Henriques, 2004), while not taking the full lifecycle of products into account, and even do not regard waste materials management as a key business area. In addition, studies have shown that smaller organizations pay less attention to "waste prevention" or "cleaner production" than larger ones (European Environment Agency, 2003).

In this Chapter, how game theory offers an approach to model the behaviour of companies under different policy scenarios is illustrated. A simple 'cleaner production' game is presented in which Government and Manufacturers are the principle 'actors'. The starting point of this approach is to analyze the possible game situation, including the dilemmas and actions available to government and manufacturers, respectively, and then provide a "Two-Person Non-cooperative" game model based upon the analysis of the problem situation behind the cleaner production game. Moreover, the 'Gambit' software tool is used to simulate the created game model followed by a number of set scenarios, in which government and manufacturers' actions are determined mainly by governmental policy of economic sanction, cost of technological innovation and expected sales profit, whilst maintaining governmental subsidy (tax break) constant. Scenario analysis generated by the established game model can provide a guide to policy makers.

5.2 Game situation analysis

In order to evaluate the 'problem situation', a conceptual model by means of 'CATWOE' analysis is developed in this section, to understand the principal drivers, actors, *etc.* and influences upon the ultimate environmental impact involved in a 'game'. The 'CATWOE' analysis is derived from the soft systems methodology (SSM) which is assembled by the sequential process, root definition (RD) and conceptual model (CM) (see Fig.5.1). The root definition defines aim of system, *i.e.,* what the system is, whilst the conceptual model presents what the system should do, *e.g.,* the activities which should be done in accordance with the purpose (Wilson, 2001). Moreover, the 'CATWOE' analysis selects the words from the RD and should be a test of the structure, providing a useful mnemonic which can be used to stimulate thinking about problems and possible solutions (Checkland, 1990; Wilson, 1990).

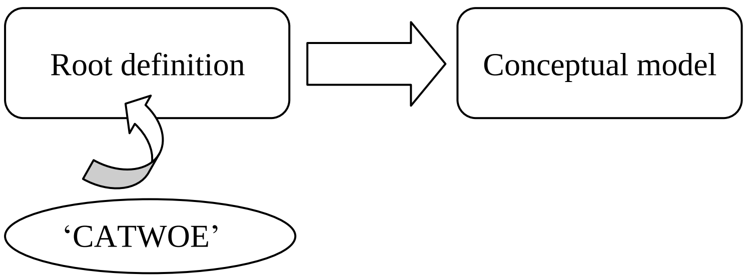

Fig.5.1. Process of the Soft System Methodology
(Adopted from: Checkland and Scholes, 1990)

There are six important elements of ‘CATWOE’, which can be specified as followed (Checkland, 1990; Wilson, 1990):

C -‘Customers’: the client, beneficiary or victims, *i.e.,* who are the beneficiaries of the transformation process and how does the issue affect them.

A-‘Actors’: the agents who would carry out or cause to be carried out the transformation process, *i.e.,* who is involved in the situation, who will be involved in implementing solutions.

T- ‘Transformation Process’: the conversion of input to output, *i.e.,* what processes or systems are affected by the issue.

W- ‘World View’: the outlook or taken for granted framework which makes the transformation process meaningful, *i.e.,* what is the big picture and what are the wider impacts of the issue.

O- ‘Owner’: ownership of a system, control, concern or sponsorship, *i.e.,* who owns the process or situation being investigated and what role will they play in the solution.

E- ‘Environmental Constraints’: environmental impositions, elements outside the system, interactions with wider system, *i.e.,* what are the constraints and limitations that will impact the solution and its success.

In this research, the root definition is deemed as “manufacturers, supervised by government, to provide environmentally friendly products for publics, by reducing the environmental risk and carbon footprint, as well as enhancing the economic performance”. Here, the representative implication for ‘CATWOE’ can be found as followed:

C- Publics (Societal members)

A- Manufacturers

T- Provide ‘environmentally friendly products’

W- Reduce the environmental risk and carbon footprint, as well as enhancing the economic performance, followed by ‘Triple Bottom Line’ (TBL)

O- Manufacturers and Government

E- Not specified (including additional capital paid for upgrading the existing equipment, technology *etc*)

Thus, a conceptual model is built to discuss the potential game situation followed by the above root definition (See Fig.5.2), which could be the premises to analyze the possible actions between government and manufacturers in the context of ‘cleaner production’ or the supply chain network (will be detailed in the Chapter 6). This game problem primarily results from the product development responding to the public’s pull and the resulting consumption. Moreover, it is important to note that commercial products are sometimes manufactured using materials that are potentially ‘hazardous’, from which public health can be affected because of the inherent risk, and in some cases the health effects can be substantial. For instance, many materials have potential for toxicity, especially cancerogenesis or lead to long term chronic health effects, such as formaldehyde which is a common substance used in some furnishings. Accordingly, members of the public can be at a finite risk from everyday consumer products. However, the public are prepared to accept this risk on account of the useful value of the products, the balance between risk and reward being a key element of subjective risk. In this context, it is important to note that a decision making process for production which does not take subjective risk into account may result in an inappropriate solution that will not meet with public acceptance (McGuire, Neighbour and Price, 2010). Therefore, the 'better and safer' alternatives to consumer products are demanded by the public. Meanwhile, the manufacturers find huge commercial opportunities or advantages through the improvement of their environmental performance. With 'green consumerism' gradually emerging into the mainstream market, the governmental incentives and the consumer behaviours could be more rational. Thus, an unprecedented business opportunity would have been created for both "environmentally sound products" and services. In this case, public demand is deemed to be the 'principal driver' in the cleaner production 'game' situation. In the following sections, to illustrate the approach being taken, different stakeholders, *i.e.* Government and Manufacturers, with a large area of common interest are analysed to present their opportunities and dilemmas.

5.2.1 Governmental action and dilemma

The Government role, is seen as promoting environmental protection to create a genuinely sustainable society, whilst safeguarding economic development overall, which can be integrated into the concept of the "Triple Bottom Line" (DEFRA, 2009). TBL provides an interpretation of the concept of 'sustainability' that, focuses not only on economic value, but also on environmental and social impacts that organisations have it in their power to influence (Elkington, 1997).

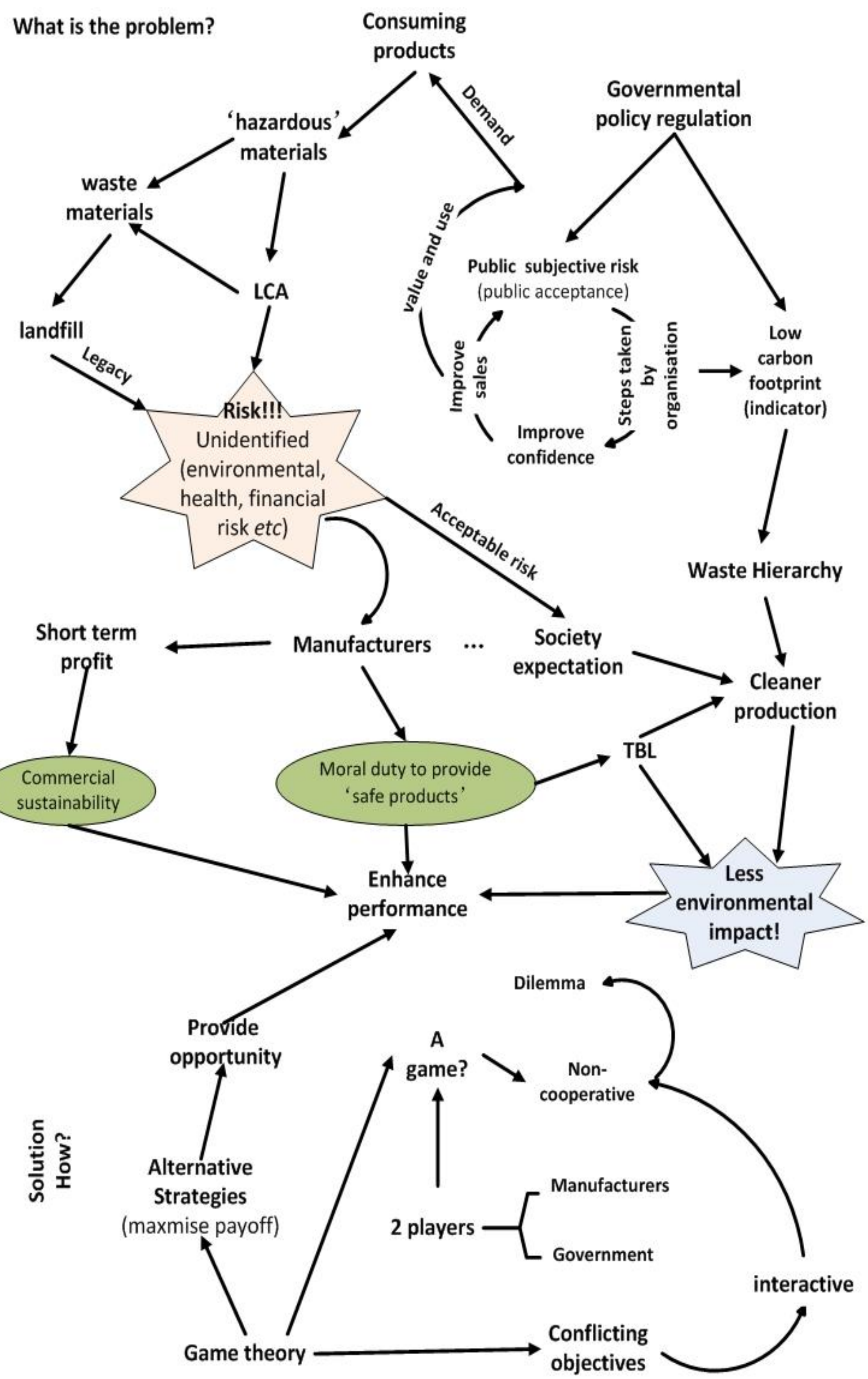

Fig.5.2. Conceptual model of the game situation

With regard to the 'cleaner production', government aims to "*encourage and drive innovation, research and design, in order for sustainability improvements throughout the lifecycle of all kinds of products"* (DEFRA, 2008). To be more specific, the main actions that government can undertake to intervene in the process of 'cleaner production' are to prohibit the sale of those least sustainable products in the market; drive the existing market towards more sustainable products through regulation; encourage the development of 'better' and sustainable products through regulation, knowledge transfer, improved design and subsidy.

Fig.5.3 shows the above main actions in a product distribution curve. With the development of intervention, the whole product and market would become more sustainable over time. Furthermore, these actions mainly are enforced by using policy regulation, investing in environmental education for the public, funding for research and development for new technologies, research and the exploitation of knowledge, working with business on innovation in the environmental industries sector *etc*, to prevent or minimize environmental impact and public subjective risk, thus to achieve cleaner production by providing "environmentally friendly products". Moreover, game theory allows this model to be tested more thoroughly as well as provide an approach to determine the most dominant strategy in the market taking account of the triple bottom line.

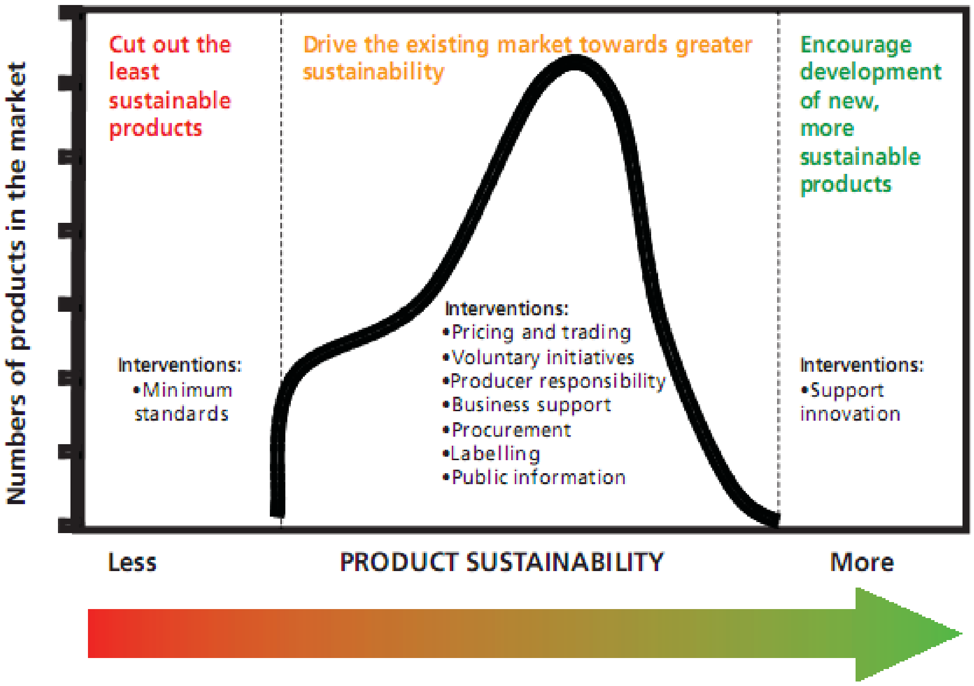

Fig.5.3. Possible Government interventions to increase sustainability (Adopted from: DEFRA, 2008)

However, there are also some dilemmas that affect government actions during the process of 'cleaner production'. Primarily, the potential conflict between economic performance and environmental impact should be taken into account at an early stage, as far as the difficulties of policy implementation are concerned. Other uncertain aspects include the dynamic behaviour of the system, *e.g.* the unintended consequences of the regulation involved, environmental impact, social responsibility, company behaviour, *etc*. It should be noticed that although relevant fixed legislation are being formulated to drive industry towards sustainability, these inflexible regulations will only intensify in number and scope, if manufacturers do not respond (Kane, 2010). Given the complexity, there are also "incentives or sanctions": how should Government establish the reasonable incentive and restraint mechanism? For example, revenues from the landfill tax can be used to fund programmes to support business in improving resource efficiency (DEFRA, 2006).

5.2.2 Manufacturers' action and dilemma

For the manufacturers, there are three levels to run a business from bottom to top, which can be described as basic market demand (bottom line), a sustainable source of raw materials and energy for production, and gradually achieving 'green' societal value for environmental protection (Kane, 2010). The manufacturer's role is to promote their individual firm's economic stability whilst acting in accordance with policy and norms of behaviour. With the implementation of clean production technology, manufacturers should recognize that they need to take more corporate social responsibilities (CSR) for the public rather than just their own profitability. For instance, some blue chip organizations are using the Triple Bottom Line to manage their production processes. Moreover, corporate governance, risk management and control, business accounting and reporting can be enhanced by CSR implementation to varying degrees (Monagban, 2004).

However, manufacturers are also faced to the dilemma that challenges and opportunities coexisting with the risk and success, thus not easily to change their business strategies. Any change to strategy provides an additional risk, but this may be offset by punitive measures where manufacturers could be punished for environmentally unfriendly production, for instance, higher carbon footprint for the products *etc*. The question becomes should manufacturers pre-empt regulatory action and seek to gain a competitive advantage or key selling point by considering the TBL. The traditional basis on which companies operate is governed by the profit motive, hence there has been a tendency to neglect their higher moral responsibility to provide 'environmentally sound' and 'socially responsible' products having due regard to the Triple Bottom Line (TBL).

5.3 Game model for cleaner production

At its simplest, a "Two-Person Non-cooperative" game model for cleaner production is built with two players: Government (G) and Manufacturers (M), respectively. This model starts from the consideration of 'fiscal measures' by Government and 'cost-benefit analysis' by manufacturers in the process of cleaner production. Suppose each of them has two available strategies. For government, the strategies are: {R, NR} which indicate whether government should regulate (R) manufacturing process and market competition in order to promote cleaner production or not regulate (NR), while keeping the current relationship between supply and market demand. Correspondently, there are two strategies for manufacturers, which are {CH, NCH}. Action CH means that manufacturers decide to change (CH) their existing process technology or equipment aiming at better product quality and market expansion, whist NCH means no change to existing business practices. Table 5.1 shows the expected payoffs for the two players with different actions.

Table 5.1 Payoffs matrix between Government (G) and Manufacturers (M)

M \ G	CH	NCH
R	$E\text{-}T_B$, $T_B\text{-}C+S$	$P\text{-}I$, $-P$
NR	E, $-C+S$	$-I$, 0

In the payoffs matrix, 'T_B' corresponds to the governmental subsidy in a form of 'tax break' in order to help manufacturers implement cleaner production; 'P' denotes economic penalties if manufacturers still insist on environmentally unfriendly production, and 'C' represents the cost of technological innovation of manufacturers for cleaner production. 'E' denotes the economic benefit that government would gain in terms of revenue when manufacturers improve production technology, whilst minimizing environmental impact, such as reducing environmental risk and carbon footprint *etc*. 'S' indicates the additional sales that manufacturers may expect from adopting cleaner production instead of the existing method of production. 'I' denotes the possible loss resulting from environmental impact (such as pollution events).

It is considered that the dilemma between Government and Manufacturers is an "imperfect information game". A game with imperfect information is defined as *"one in which neither player knows the actions of the other player before playing his or her own strategy"* (Fink, 1998). In this game, manufacturers cannot predict the actions taken by government at an earlier stage of the game. However they may pay more attention to the potential economic benefits while choosing to change or not to change. Meanwhile, government initially cannot determine whether to regulate the market or not, as the actions from manufacturers could be cooperative or non-cooperative. Therefore, a game with imperfect information adds to the complexity and uncertainty of the game.

5.4 Game theoretical analysis

According to the above payoffs matrix (See Table 5.1), game theoretical analysis is introduced in this section to predict the possible actions of government and manufacturers, respectively, which will be a basis for further simulation in different game scenarios.

5.4.1 Strategic action of manufacturers

The functions of the expected payoffs of manufacturers can be easily derived by assuming that government takes the action of "Regulation". When the strategy 'CH' (Change) or 'NC' (Non-change) has been selected, the functions of expected payoffs can be expressed as V_{CH} and V_{NC}, separately. The expressions of expected payoffs can be seen as following:

$$V_{CH} = (T_B - C + S) \times \Pr ob\{G = R\} \quad (5\text{-}1)$$

$$V_{NC} = -P \times \Pr ob\{G = R\} \quad (5\text{-}2)$$

where $\Pr ob\{G = R\}$ is the probability that government takes the action of 'Regulation' (R).

In order to aid manufacturers change the current mode of production, followed by implementation of cleaner production as the dominant strategy, the relationship between Equations (5-1) and (5-2) should be satisfied as $V_{CH} > V_{NC}$. Thus, $V_{CH} - V_{NC} > 0$ and the following inequality can be derived.

$$(T_B - C + S + P) \times \Pr ob\{G = R\} > 0 \quad (5\text{-}3)$$

No matter what of $\Pr ob\{G = R\}$ value is selected (from 0 to 1), deemed as no matter how efficient government regulation is (to what extent that government will take regulation into account), we still seek $(T_B - C + S + P) > 0$. This inequality can be transformed into the following inequality:

$$C - P < S + T_B \quad (5\text{-}4)$$

Thus, if the difference between addition cost (C) that manufacturers will pay for technical innovation and essential economic fine (P) is lower than the sum of additional sales (S) of "environmentally friendly products" and Tax Break (T_B) that government provides in order to promote "cleaner production", manufacturers will prefer "Change" (CH) rather than "Non-change" (NCH).

Assuming that government will choose the action of "Non-regulation" (NR), the expected payoff $V_{CH}{}'$ can be obtained as followed, if manufacturers determine to change their existing production mode.

$$V_{CH}{}' = (-C + S) \times \Pr ob\{G = NR\} \qquad (5\text{-}5)$$

where $\Pr ob\{G = NR\}$ is the probability that government takes the action of 'Non-Regulation' (NR).

Only if the Equation (5-5) be greater than 0, will manufacturers follow the implementation of cleaner production (CH). Moreover, $S > C$ can be derived from Equation (5-5), which indicates that the additional sale for 'environmentally friendly products' could cover the additional cost for technical innovation.

The inequality (5-4) can be transformed into inequality (5-6) as followed:

$$P + T_B > C - S \qquad (5\text{-}6)$$

Since $S > C$, $C - S$ should be lower than 0, $P + T_B$ should be definitely greater than the difference between C and S. From inequality (5-6), it is identified that no matter what government will choose, the action of 'change' (CH) is the strictly dominated strategy for manufacturers.

5.4.2 Strategic action of government

The functions of the expected payoff for governmental regulation "U_R" and non-regulation "U_{NR}" can be expressed in Equations (5-7) and (5-8), respectively.

$$U_R = (E - T_B) \times \Pr ob\{M = CH) + (P - I) \times \Pr ob\{M = NC) \quad (5\text{-}7)$$

$$U_{NR} = E \times \Pr ob\{M = CH) - I \times \Pr ob\{M = NC\} \quad (5\text{-}8)$$

where $\Pr ob\{M = CH)$ is the probability that manufacturers takes the action of 'Change' (CH), whilst $\Pr ob\{M = NC)$ is the probability that manufacturers takes the action of 'Non-change' (NC).

In the above equations, $\Pr ob\{M = CH) = 1 - \Pr ob\{M = NC\}$ implies the sum of probability is equal to one that manufactures choose either the actions 'Change' or 'Non-change'. Moreover, the difference can be derived by subtracting the Equations (5-7) and (5-8), shown as followed:

$$U_R - U_{NR} = P - \Pr ob\{M = CH\} \times (P + T_B) \quad (5\text{-}9)$$

If Manufacturers definitely choose to change their existing mode of production, $\Pr ob\{M = CH) = 1$, $U_R - U_{NR} = -T_B$. Thus, the best choice for government is not to offer any subsidy for manufacturers. In this case, if manufacturers choose to 'Change' (CH), they will gain $S - C$. Otherwise, they will gain 0 followed by the action 'Non-change' (NCH).

5.5 Simulation of game situations

According to the above theoretical analysis, three possible game scenarios are presented in sequence to select different pairs of strategies. These game scenarios are generated by inserting different numerical values in terms of a logic unit. In this section, a simulation software tool ‘Gambit’ (McKelvey, McLennan and Turocy, 2007) is used to express the dilemma and possible game actions between government and manufacturers. Gambit is an effective tool to construct and analyze certain extensive and strategic games, while with the latest and ultimate version 0.2007.12.04 released on 4th December 2007 (McKelvey, McLennan and Turocy, 2007). Currently, specific software or tools for Game theory solution are rarely reported in the literature. There are several advantages of Gambit which are presented below to demonstrate why it is selected for the simulation:

1. Gambit is an open source free software for game theory simulation, through which users are allowed and encouraged to apply the functions provided for their own requirements.

2. Gambit supports multiple platforms, including Windows XP, Linux, MacOS X etc, with C++ source code for representing games.

3. Gambit can distinguish the documented file formats, which make them be able to interact with other external platforms, as implementing new computing methods for game analysis.

4. All the game programs are encapsulated in an integrated and user friendly interface, in which the functions can be invoked easily by users to simulate the game and analyze the results.

5. From the standpoint of programming for game analysis and simulation, Gambit could save the cost and time for users making the same programming to solve similar game problems.

However, there are still some limitations in this intelligent software.

1. If a game should be the infinite game, in which players would choose continuous and different types of strategies, Gambit cannot simulate a solution out as its mathematical structure for finite games, and moreover the computer cannot run infinitely.

2. Cooperative game theory is still a hot issue being discussed in the academic field of game theory, especially some problems within do not suffer from computational complexity but could be resulted from game rules which are not very clear, for instance the player's actions maybe interacted with each other. Thus, Gambit can only support non-cooperative game theory.

3. Gambit cannot deal with periodic games or evolutionary games, instead of one-off games, as the Nash equilibrium can be difficult to compute with the varying strategies.

In summary, all the built strategic game models could be solved using the Gambit software package and it will be embedded into a larger, more developed decision support tool called 'Environmental Risk management System for Hazardous Waste Materials' in this study.

5.5.1 Game scenario one

Game scenario one illustrates the preliminary stage of the game situation, which reflects the difficulty in developing a cleaner production program. For government, the supervision and regulation of cleaner production is still insufficient with ambiguous policies of sanctions and incentives. Furthermore, any new change may also give rise to an economic risk for the manufacturer. For instance, if the additional sales of environmentally friendly products can not initially cover the total economic cost, manufacturers will be reluctant to implement cleaner production. Thus, once $S - C + T_B < -P$, manufacturers will prefer paying the penalties for environmentally unfriendly production. Selected model parameters for game simulation are presented in Table 5.2. Here, in order for wider application, all the parameters are expressed in terms of a logic unit. For example, costs may be indicated as 1 unit to represent the real monetary value. The tax break can be provided in terms of 'Capital allowance', currently around 20% in UK for plant and machinery (UK HM Revenue & Customs, 2008), and it is assumed in this model 22 percent of the technological innovation cost can be saved by upgrading the existing machinery, equipment or tools to promote cleaner production. The factor on revenue and additional sales can be random variables, 10 to 10000 times more than the cost in order for sensitivity analysis. In this scenario, we assume that additional sales can cover 50% of the cost at most (0.1 to 0.5). Moreover, the fine factor related to economic sanctions needs to be set at a very low level (0 to 0.2), which is estimated by the equation $S - C + T_B < -P$, as well as the value range of additional sales factor (S). Otherwise, if the penalty for manufacturers is set at a higher level, manufacturers would mostly opt for a production change for their strategic action. Thus, the dominant strategy pair will be (R, NCH).

Table 5.2 Model parameters of game scenario one

Parameters	Conversion factors	Note
Cost (C)	1 unit	
Tax Break (T_B)	Cost×22%	Rand is a function which the random number from 0 to 1 will be selected.
Economic Benefit (E)	Cost×Rand×Revenue factor	Revenue factor is between 10 to 10000
Additional Sales (S)	Cost×Rand×Sales factor	Sales factor is between 0.1 to 0.5
Economic Sanction (P)	Cost×Rand×Fine factor	Fine factor is between 0 to 0.2
Environmental Loss (I)	Cost×Rand×Loss factor	Environmental loss factor is 10000

Once the model parameters have been determined by Table 5.2, the Nash Equilibrium is stable and will not vary no matter how many times the game model is run. Thus, a random group of numerical value has been selected to represent the game situation by means of the 'Gambit' tool (see Fig.5.4a). In the Gambit tool, the dominated strategies can be eliminated iteratively by the dominance panel. The strictly dominated action is opposite to dominant strategy, which is defined as "always worse than another, regardless of beliefs at the information set" (Mckelvey *et al.,* 2010). In this scenario, CH is the strictly weak strategy for manufacturers which should be eliminated first (see Fig.5.4b). When manufacturers determine not to change their current production mode, non-regulation becomes the dominated strategy accordingly. Fig.5.4c shows the second round of dominated strategy elimination, in which 'NR' has been crossed out. The pair of dominant strategy comes out since all the dominated strategies have been eliminated. In scenario one, the result in Fig.5.4d suggests that government should regulate the manufacturing process by selecting 'R', while the manufacturers' position remains unchanged ('NCH') due to the insufficient economic sanctions.

The remaining strategy pair (R-NCH) represents the unique and stable Nash Equilibrium for this game solution. Moreover, this is a pure strategy game, which is a game with probability of one given to the selected strategy and zero to others (Romp, 1997). For instance, Fig.5.5 shows the computation result of Nash Equilibrium, from which the probability equals to one when government chooses 'R' and manufacturers choose 'CH'.

The traditional method of computing the Nash Equilibrium is strongly deterministic. However, the 'Gambit' tool provides a novel approach called 'Quantal Response Equilibrium' (QRE) to search the subset of Nash equilibria. This approach uses imperfect or noisy expectations logic instead of the perfectly rational expectations logic, when searching for the Nash Equilibrium (McKelvey and PalFrey, 1995). Fig.5.6 demonstrates how the 'QRE' approach is used to search Nash Equilibrium. The QRE model is a function of a probability distribution and the error of choice selection, Lambda (λ) in the figure is related to the level of error in expectation. For $\lambda = 0$, the actions are composed of errors, and for $\lambda \to \infty$, there is no error. If both players, government and manufacturers, evaluate their expected payoffs in an unbiased way, the probabilities of each strategy being selected should be the same at the beginning of the game, that is why all the graphs in Fig.5.6 start at 0.5. As Lambda tends to infinity (∞), the Nash Equilibrium converges to a unique value. For example in this game scenario, the pair of Nash Equilibrium is 'R-NCH', as well as the probability of selecting both strategic actions, equals to one (See Fig.5.6a and Fig.5.6d).

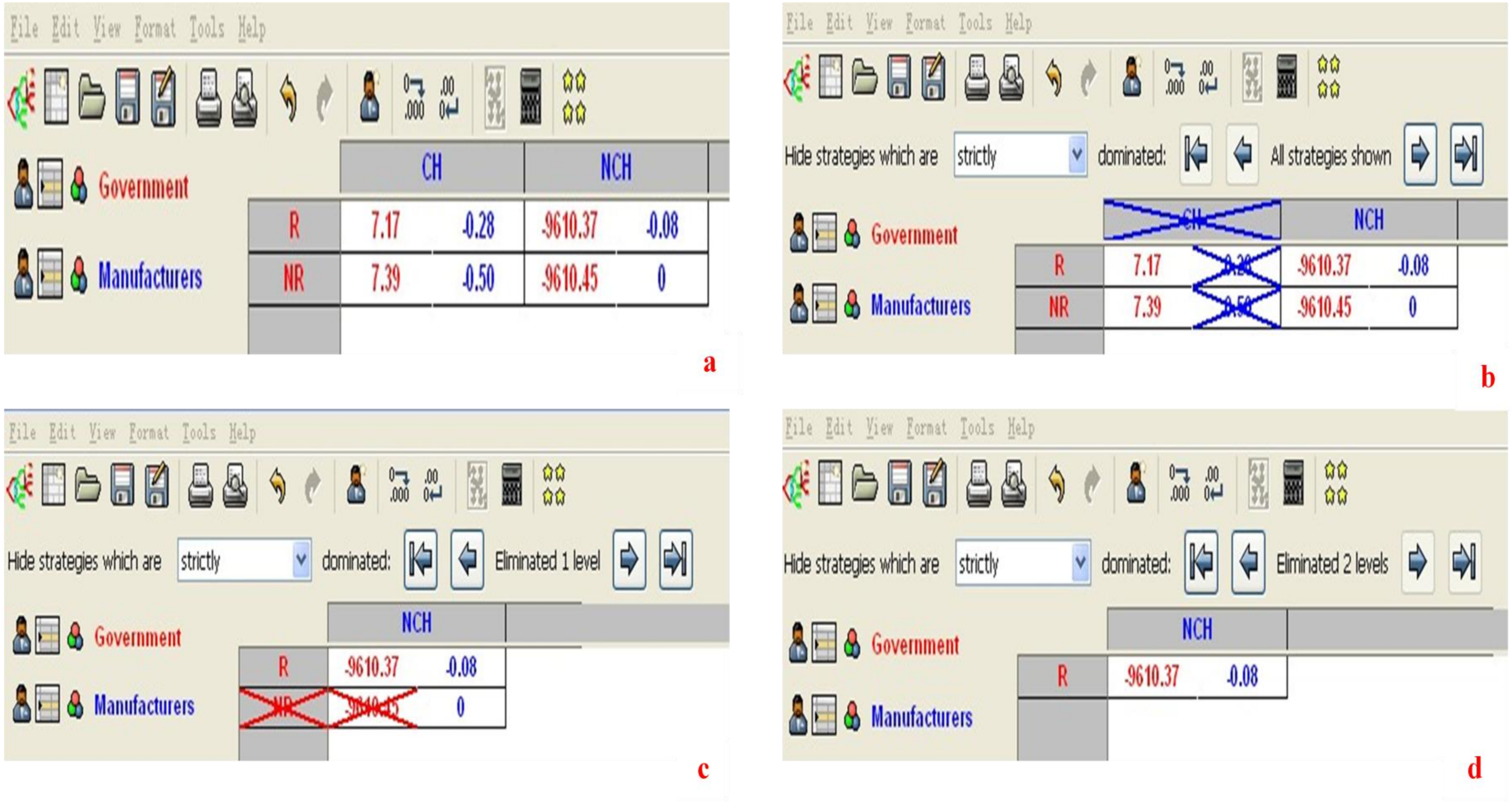

Fig.5.4. Gambit simulation for game scenario one

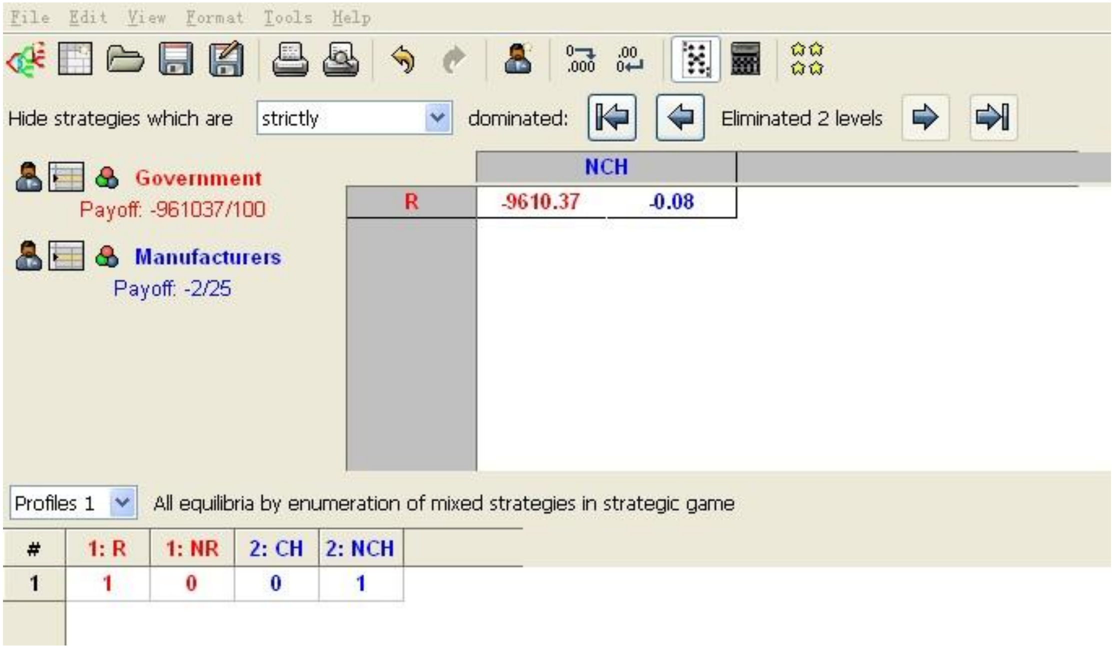

Fig.5.5. Computation result of Nash Equilibrium in game scenario one

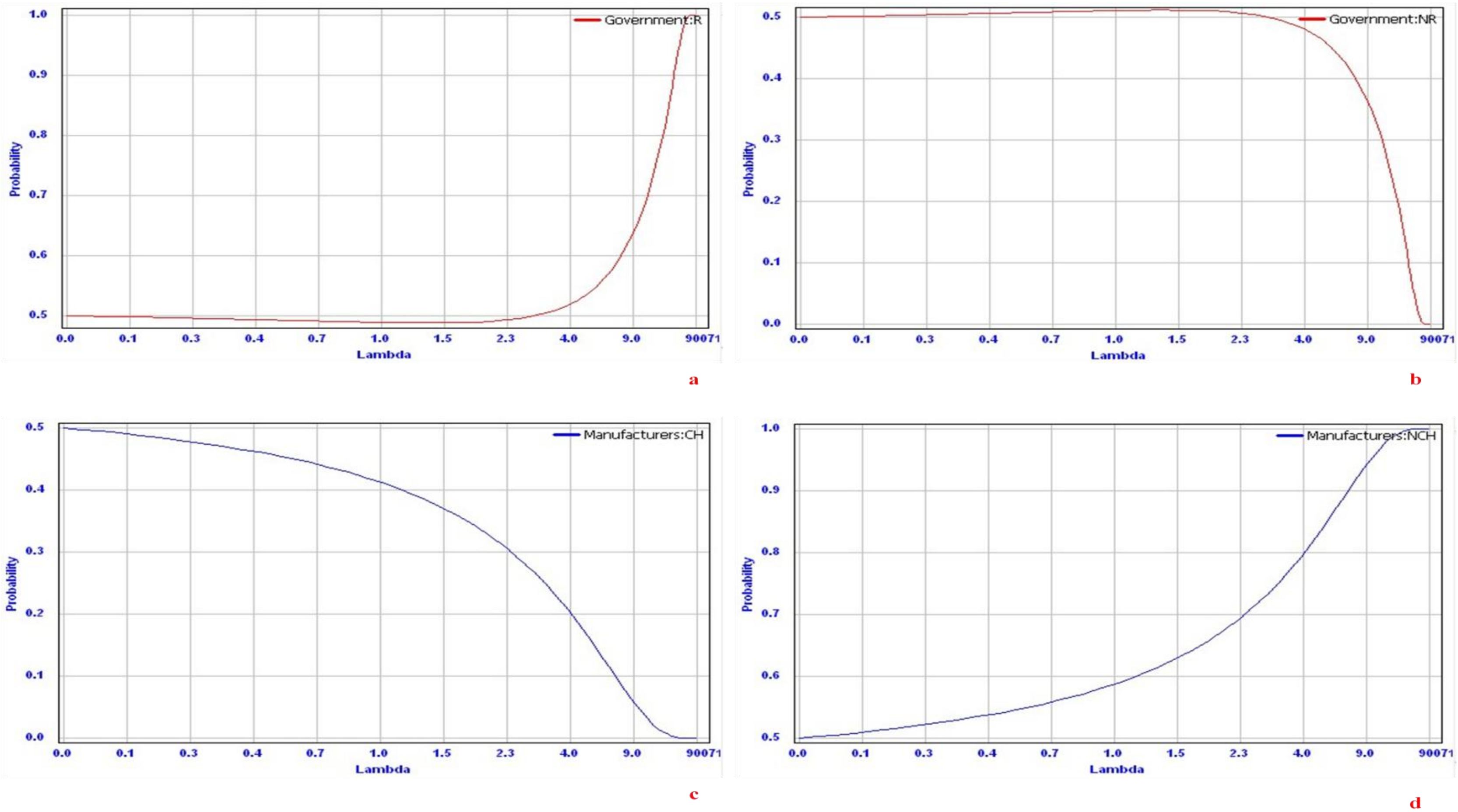

Fig.5.6. Quantal response equilibrium approach for game scenario one

5.5.2 Game scenario two

Without sufficient governmental regulation for industrial production, society could be exposed to serious environmental impact. If government imposes heavier economic penalties (P) for environmentally unfriendly actions, manufacturers are again obliged to compare the payoff in implementing cleaner production (CH) with that of keeping existing methods (NCH), in order to identify the most beneficial strategy. Game scenario two suggests that if $S - C + T_B > -P$, there is no dominant strategy in the game. Thus, a mixed-strategy game scenario is generated to find out the corresponding Nash Equilibrium. A mixed-strategy equilibrium, in contrast to pure strategy equilibrium (each player can only select one specific strategy in a game), is defined as "*at least one player involved in the game will place a probability distribution for the alternative strategies*" (Romp, 1997). Table 5.3 reflects the parameters selected for game scenario two, especially assuming that the economic penalty (P) for environmentally unfriendly actions is set to severe, *i.e.* weighted as 10000 times more than cost.

Table 5.3 Model parameters of game scenario two

Parameters	Conversion factors	Note
Cost (C)	1 unit	
Tax Break (T_B)	Cost × 22%	Rand is a function which the random number from 0 to 1 will be selected.
Economic Benefit (E)	Cost × Rand × Revenue factor	
Additional Sales (S)	Cost × Rand × Sales factor	Revenue factor is between 10 to 10000
Economic Sanction (P)	Cost × Rand × Fine factor	Sales factor is between 0.1 to 1 Fine factor is 10000
Environmental Loss (I)	Cost × Rand × Loss factor	Environmental loss factor is 10000

Fig.5.7 reflects the variation of Nash Equilibria as calculated by the ‘Gambit’ tool, with the sales factor being varied from 0.1 to 1. It can be found that the probability that government chooses ‘Non-regulation’ (NR) while Manufacturers choose ‘Change’ (CH) is nearly 1, about 99%. This pair of strategic selection (NR-CH) approximates closely to the dominant strategy selected in game scenario three, which will be demonstrated in the following section. Moreover, this selection is strongly determined by governmental sanction. Manufacturers will consider changing their current industrial process by upgrading the existing equipment or technology for cleaner production, only if the economic penalty is set high enough (as 10000 shown in Table 5.3).

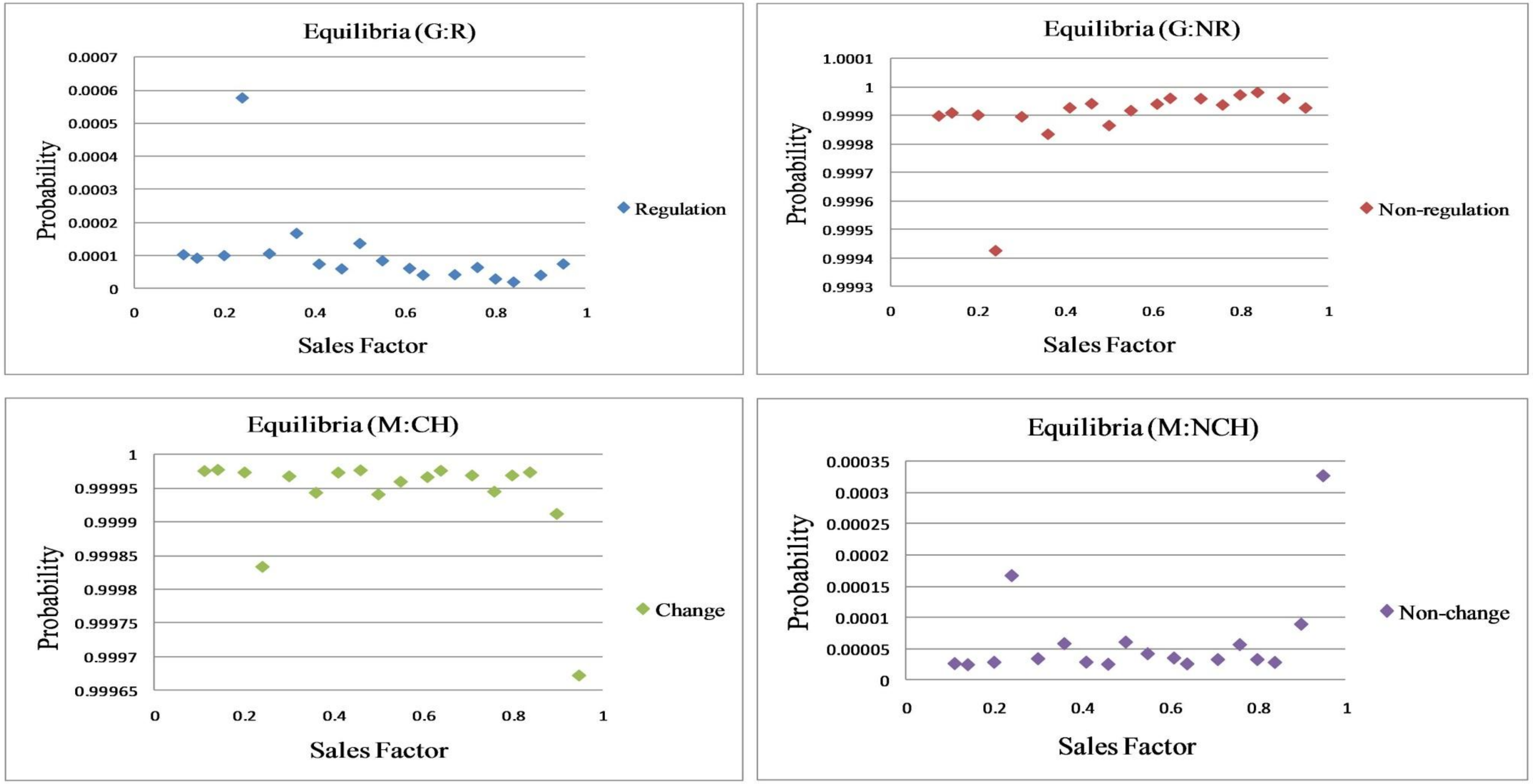

Fig.5.7. Nash equlibria of game scenario two

5.5.3 Game scenario three

With "green consumerism" gaining increasing influence on the market, so will cleaner production mature correspondingly, and thus manufacturers will gradually seek to benefit from business opportunities connected with sales of 'environmentally friendly products'. Once the additional sales completely cover the total cost ($S > C$), government will no longer need to take actions to regulate the process, with manufacturers opting to develop cleaner production voluntarily. This game scenario suggests the dominant strategy is that government chooses 'NR', and manufacturers choose 'CH', which is the optimal result among the three game situations. Table 5.4 summarizes the conversion factors to determine the model parameters. As long as 'additional sales' (S) is above cost (C), 'NR-CH' (Non-regulation for Government, Change for Manufacturers) is the unique Nash Equilibrium of this game scenario no matter how the factors change. Fig.5.8 shows the possible maximum and minimum payoffs of strategies of 'R-CH' and 'NR-CH' with both revenue and sales factors being varied from 10 to 10000.

Table 5.4 Model parameters of game scenario three

Parameters	Conversion factors	Note
Cost (C)	1 unit	
Tax Break (T_B)	Cost×22%	Rand is a function which the random number from 0 to 1 will be selected.
Economic Benefit (E)	Cost×Rand×Revenue factor	Revenue factor is between 10 to 10000
Additional Sales (S)	Cost×(1+Rand×Sales factor)	Sales factor is between 10 to 10000
Economic Sanction (P)	Cost×Rand×Fine factor	Fine factor is 10000
Environmental Loss (I)	Cost×Rand×Loss factor	Environmental loss factor is 10000

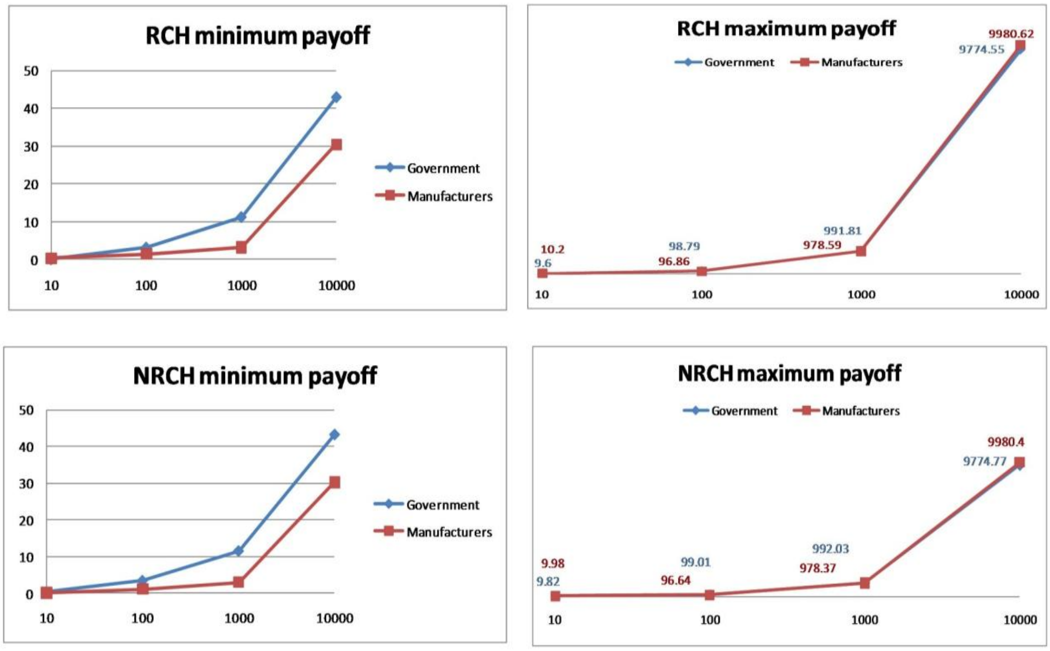

Fig.5.8. Maximum and minimum payoffs with different factors

Since $S > C$, the Nash Equilibrium will not be changed in this scenario. Fig.5.9 shows a random group of numerical values being selected to simulate the game situation by Gambit tool (assuming 10 for both revenue and sales factors in this example). Like the analysis of game scenario one, the dominated strategy and its corresponding payoff should be eliminated. Thus, Fig.5.9b shows no matter whether government choose regulation or non-regulation, 'NCH' is the weak strategy for manufacturers which should be eliminated first. When the action of 'NCH' has been eliminated in the first round, 'R' is the dominated strategy for government in the second turn whilst 'CH' is selected by manufacturers (see Fig.5.9c). Once all the dominated strategies have been eliminated, Fig.5.9d suggests that the dominant strategy is that 'NR' selected by government and 'CH' by manufacturers. This result also suggests a pure strategy pair with the probability of one being calculated for both strategy 'NR' and 'CH', respectively (see Fig.5.10).

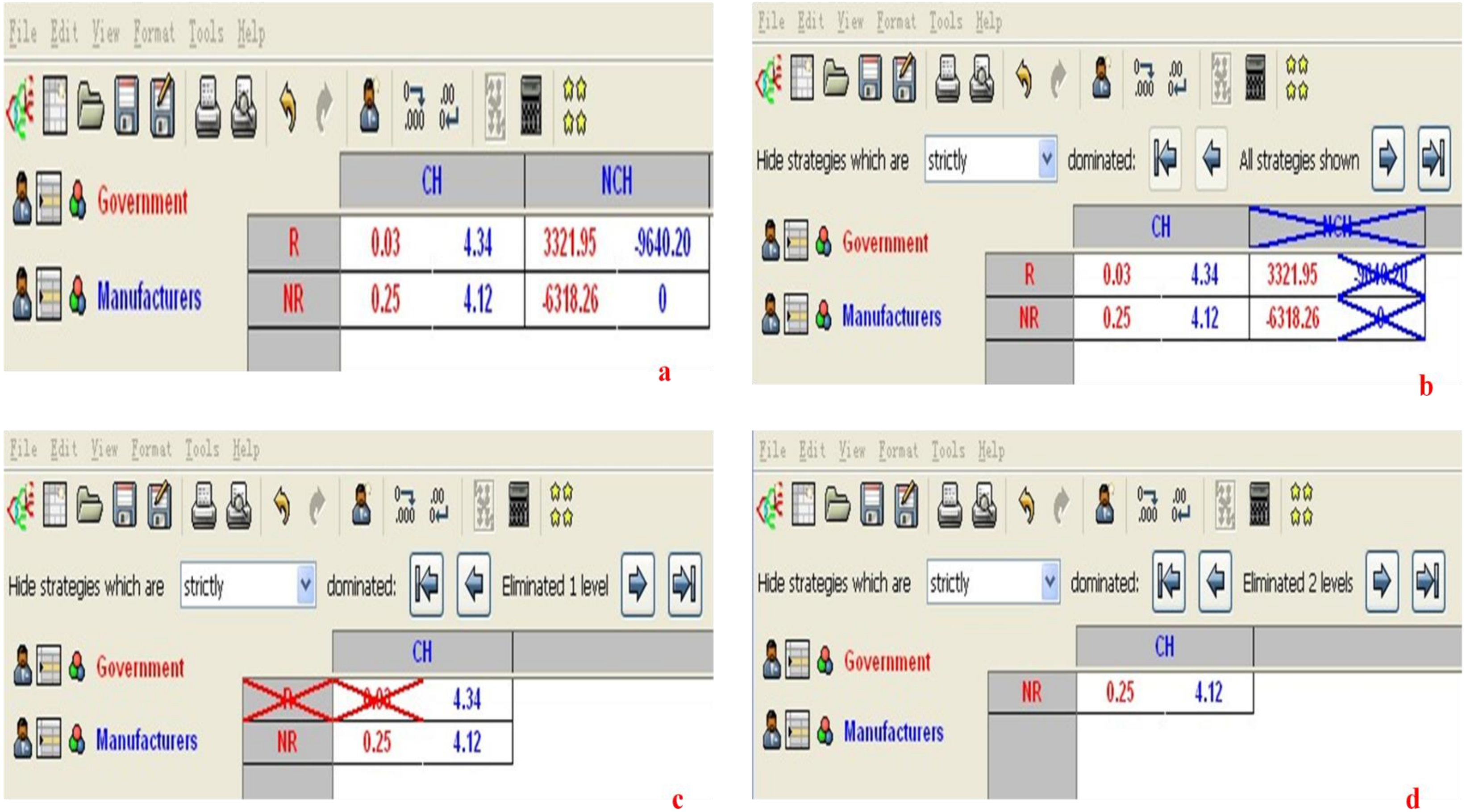

Fig.5.9. Gambit simulation for game scenario three

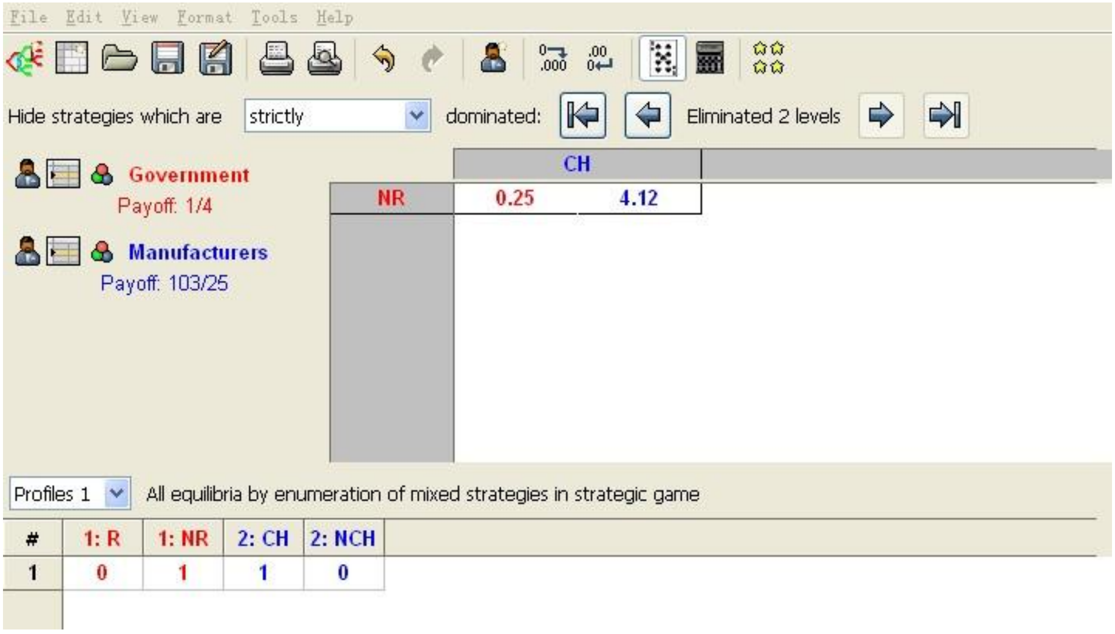

Fig.5.10. Computation result of Nash Equilibrium in game scenario three

As an analogy to the first game scenario, 'QRE' approach can be also applied to this scenario in order to search for the unique Nash equilibrium. Fig.5.10 reflects that the strategic action pair 'NR-CH' is the unique and stable solution of Nash Equilibrium found by the 'Gambit' tool. In contrast, the 'QRE' curves shown in Fig.5.11, which present the steady trend of rising or declining probability, have fluctuated at first and then stabilized. For example, when government chooses the action of 'R', the probability firstly ascends from 0.5 to above 0.6 and then regresses, finally falling down to 0 (See Fig.5.11a). This phenomenon results from the principle of maximum benefits followed by different actions of Government, 'R' and 'NR' respectively. From the payoff matrix in the game scenario three, it can be seen from Fig.5.9 that government can gain the maximum benefit while choosing 'R' to the extent of 3321.95 logic unit. That is why the probability of 'R' has shown an upward tendency from 0.5 to 0.6 in Fig.5.11a. However, when taking the possible actions of manufacturers into account, *e.g.* 'CH' being selected, the individual rational behaviour reminds government to re-consider the payoffs. By contrast, government can gain more benefit as 0.25 logic unit followed by selecting 'NR'. Thus, the probability to choose 'R' has fallen back to 0.5, and then gradually reduced to 0.

5.5.4 Analysis of game interaction

According to the above game simulation, it can be concluded that the strategic actions that government and manufacturers will take mainly resulted from the following factors, economic penalty (P), technological innovation cost (C) and additional sales (S). Fig.5.12 illustrates the interaction between influencing factors and the strategic actions.

It is clear that the economic penalty (P) set by governmental policy needs to be high enough to compel manufacturers to change their current production mode actively, thus to implement cleaner production as well as provide 'environmentally friendly' products. The technological innovation cost (C) should be in accordance with the basic standards or principles of cleaner production, to ensure that new products are associated with reduced environmental risk and carbon footprint, and are sustainable. For food and those materials with which people will have direct contact, the criteria of production should be much stricter. The potential economic benefit on the part of manufacturers is determined by the additional sales profit (S), which will also give rise to increasing governmental revenue. Moreover, the profit accruing from additional sales is strongly determined by consumer behaviour, and attitudes to 'environmentally sound products', public acceptance, automatically determining the actions of manufacturers, *i.e.*, whether to 'Change' or 'Not change'.

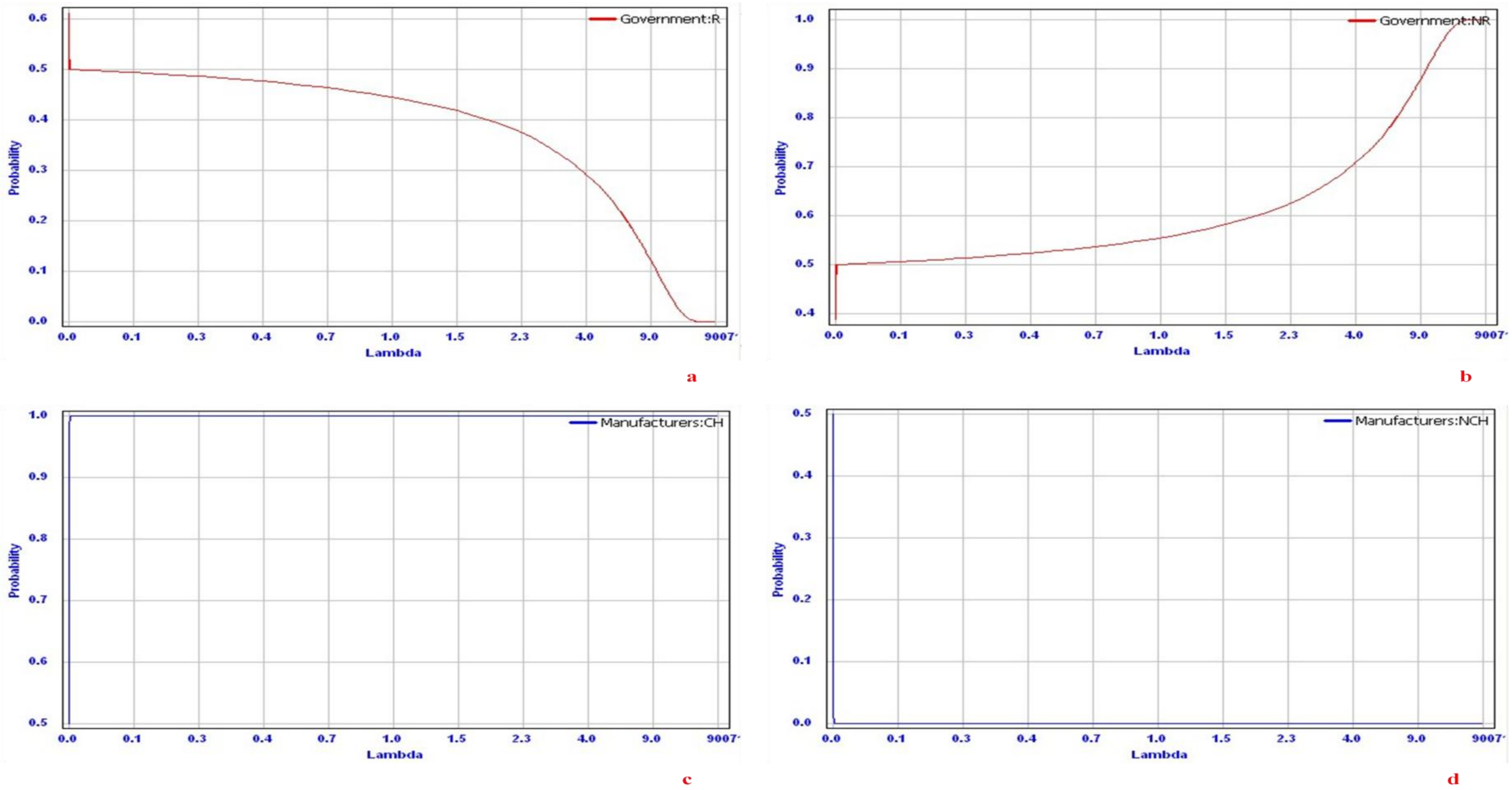

Fig.5.11. Quantal response equilibrium approach for game scenario three

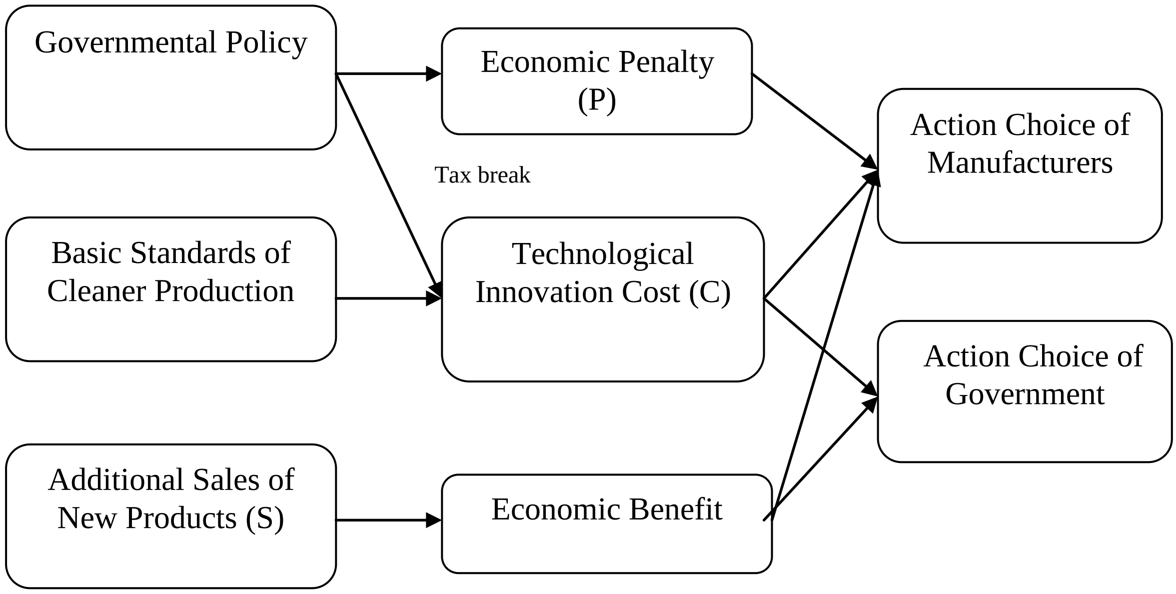

Fig.5.12. Influencing factors and strategic action

5.6 Summary

This Chapter shows how game theory could be applied to better understand the dilemmas of government and manufacturers in the context of a 'game' to achieve more environmentally friendly products. The starting point of this novel approach is to analyze the dilemmas and possible actions available to government and manufacturers by means of the 'CATWOE' approach, respectively. In order to demonstrate the problem situation of cleaner production more intuitively, the 'Gambit' tool is used to simulate the created game model conceived as a "two person non-cooperative" game.

With the improvement of cleaner production, different game scenarios have been generated to reflect the variation trend of strategic actions. The simulation result confirms that government seeks to regulate (R) the process in the initial stage of cleaner production, while manufacturers do not change (NCH) the existing production mode

(‘R-NCH’) due to any potential economic risk. As long as the penalties are set high enough, manufacturers should opt to change their production technology to be more ‘green’, and government will gradually adjust the regulatory policy. Once the ‘environmentally sound products’ have become the mainstream of market, the dominant strategy ultimately becomes non-regulation for government and change for manufacturers (‘NR-CH’), because manufacturers are then willing to promote cleaner production to gain increased profits, additional sales covering the total of technological innovation, equipment upgrading *etc.*

The application of game theory is shown to provide a useful insight to inform strategic decision making in both government and manufacturers. Chapter 6 mainly focuses on the game theory application in the context of supply chain network, to analyze the strategies selected by the manufacturers of the ‘hazardous’ materials, by reducing the environmental risk and the associated carbon emissions, in order to provide better and safer products.

Chapter 6: Game Theory Application to Supply Chain[3]

6.1 Introduction

Supply chain management (SCM) has been brought into academic research since the early 1980s, covering a range of control and planning applications relating to material selection, production, transportation, distribution *etc.*, as well as the potential collaboration among manufacturers, retailers and customers (Oliver and Webber, 1982; Hines, 2004; Blanchard, 2007; Harrison and Hoek, 2008). With global business developing rapidly, the increasing demand for the consumption of commercial products has greatly accelerated the depletion of resources and contributed environmental pollution. Green supply chain management (GSCM) has emerged as a response to the challenge of how to improve long term economic profits and environmental performance (Sheu, Chou and Hu, 2005). GSCM can be defined as a series of regulations and interventions in the supply chain achieved by attempting to minimize the environmental impact from the suppliers to the end users (Basu and Wright, 2008). It is also claimed to be a "win-win" strategy, through which economic benefits can be increased by reducing environmental impact (Zhu and Cote, 2004; Zhu, Sarkis and Lai, 2008).

In this context, GSCM has a substantial influence on the manufacturers within supply chain network, *e.g.* increasing both opportunities and challenges in green product development, promoting innovative product design *etc* (Wang and Gupta, 2011). As a consequence, manufacturers will be encouraged, not only to consider the economic

[3] This chapter has been accepted by the Journal of Loss Prevention in the Process Industries. See details in: Zhao, R., Neighbour, G., Han, J.J., McGuire, M., Deutz, P., 2012. Game Theory Approach to Strategy Selection for Environmental Risk and Carbon Footprint Reduction in the Green Supply Chain. *Journal of Loss Prevention in the Process Industries*. In press. http://dx.doi.org/10.1016/j.jlp.2012.05.004

benefits, but also to provide ‘environmentally sound’ products having due regard to the Triple Bottom Line (TBL). With integrating clean technologies into supply chain processes, one of the major environmental concerns is the detoxification of industrial pollutants (Wang, 2009), since many common industrial materials used in manufactured products can be considered harmful or ‘hazardous’ to the environment to a greater or lesser extent. In addition to the immediate risk posed by ‘hazardous’ materials in use, it is also important in the socio-political context to discriminate within the supply chain the “carbon footprint” which may be an increasingly used indicator of the public’s acceptance of the product, even though the environmental risk and the carbon footprint in the final disposal stage are often very high compared to other stages (Zhu and Sarkis, 2006). That is, the legacy of the product may further cause damage to the environment once the product has been declared ‘waste’. However, as the general framework of supply chain management is not usually considered (as opposed to the risk assessment of particular operations), manufacturers usually focus on the economic risk and benefits, as well as the efficiency of the supply chain. The treatment and disposal of hazardous materials is usually given little deliberation especially in the post-consuming stage (Deutz, Neighbour and McGuire, 2010).

This Chapter proposes a game theory approach that models the likely behaviour of manufacturers in response to drivers to reduce environmental risk and carbon emissions in the context of the green supply chain. Game theory application is described in more detail below, but in short, allows the identification of alternative ‘business’ strategies. However, here the emphasis is on reducing environmental risk without affecting the commercial sustainability, irrespective of any governmental or inter-governmental objectives, *e.g.* international treaty. Although the green supply chain management concept has laid stress on increasing economic returns by reducing the environmental risk and impacts (Zhu, Sarkis and Lai, 2008), the extent to which the environmental risk and carbon footprint reduction should be reasonable in the management process has not been generally discussed. In summary, this chapter here proposes a novel approach based on game theory to help manufacturers reduce the environmental risk of a supply chain containing 'hazardous' materials and the carbon footprint in the context of 'green' supply chain management. Moreover, this study provides an initial insight into how they may respond to game scenarios with and without governmental regulations.

6.2 Formulation of the game

Whilst it is evident that ultimately consumers drive the open market, *i.e.* an attractive and competitive product meeting a public need, it must also be recognized that Government, for good reason, often restricts the market by legislation or regulation, and that such action sometimes leads to unintended consequences. In this chapter, game theory will be used to investigate possible governmental intentions and their possible consequences.

The game situation can be defined by three important boundaries in the supply chain, Government | Manufacturer, and Manufacturer | Retailer, Retailer | Consumer, as show in Fig.6.1. It seems logical to apply game theory first to the dynamic boundary of Government | Manufacturer, which establishes the necessary regulation for industrial production at an early stage. Whilst an observer might conclude there is but one game, we suggest there that there are, in reality, several, related, but largely independent games. Thus, this chapter presents the game theory approach for strategy selection for the reduction of environmental risk and carbon footprint by manufacturers, initially without government supervision, and subsequently, with government supervision.

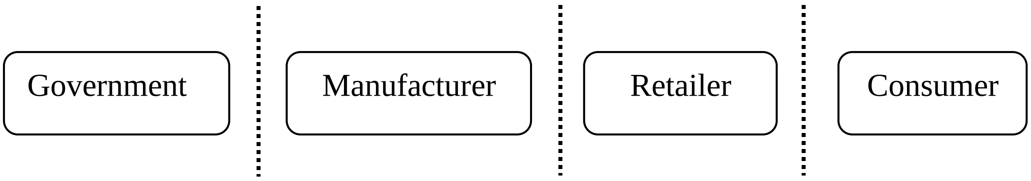

Fig.6.1. Boundaries of possible game scenarios

6.2.1 Application of tolerability of risk

As discussed in the thesis introduction, the environmental risk needs to be controlled and managed at an early stage during the production. Furthermore, in order to understand what the level of risk ought to be, as well as to estimate whether more should be done to reduce risk, it is necessary to set out certain risk criteria to determine acceptability levels ((Bouder, Slavin and Löfstedt, 2007). Thus, the principle of "tolerability of risk" provides a framework by which judgments can be made as to whether society should accept the risk (HSE, 1988). Importantly, this framework provides a benchmark for a tolerable risk, see Fig.6.2, which cannot be deemed as broadly acceptable without implementing any risk control measures, and also fills the gap between what is absolutely safe and absolutely unsafe, i.e. intolerable (Clay and Bassett, 1999). Between the intolerable region and the broadly acceptable region, it is a requirement to demonstrate the risk is 'as low as reasonably practicable' (ALARP), i.e. risk mitigation is in place. Within the ALARP region, whether to reduce the level of risk further or accept the existing level of risk can be judged on the grounds of the risk levels and the costs associated with controlling the risk (Fuller and Vassie, 2004). The principle is well established in some heavy industries, such as nuclear, chemical, etc. HSE has also proposed notional boundaries for each region (See Fig.6.2) in terms of the risk of death or serious injury to a member of the public. A risk of 1 in 10^4 per annum to any member of the public is the maximum that should be tolerated from any large industrial plant in any industry. The level of broadly acceptable risk is suggested as 1 in 10^6 per annum (HSE, 1988).

It is proposed in this study that the boundary between intolerable and tolerable regions should be represented by the 2020 carbon emission target, and that between the tolerable and the broadly acceptable region by the reduction target at the year 2050 (See Fig.6.2). According to the UK Climate Change Act 2008, the total carbon emission is expected to be reduced to, at least, 26% below the 1990 baseline by the year 2020 and 80% by 2050, respectively. The 1990 baseline represents the aggregate amount of net UK emissions of the determined greenhouse gases for that year, *e.g*. CO_2, CH_4, N_2O, HFCs, PFCs and SF_6 *etc.* (OPSI, 2008). Total aggregate anthropogenic emissions of greenhouse gases, excluding emissions from land use, land-use change and forestry, is approximately 774Mt for the UK in 1990 (United Nations, 2009). Thus, the carbon footprint at the year of 2020 and 2050 can be calculated from the 1990 baseline as approximately 572 Mt and 154 Mt, respectively. Moreover, it is proposed in this study that these emissions can be seen as the total emissions contributed by the national supply chain network.

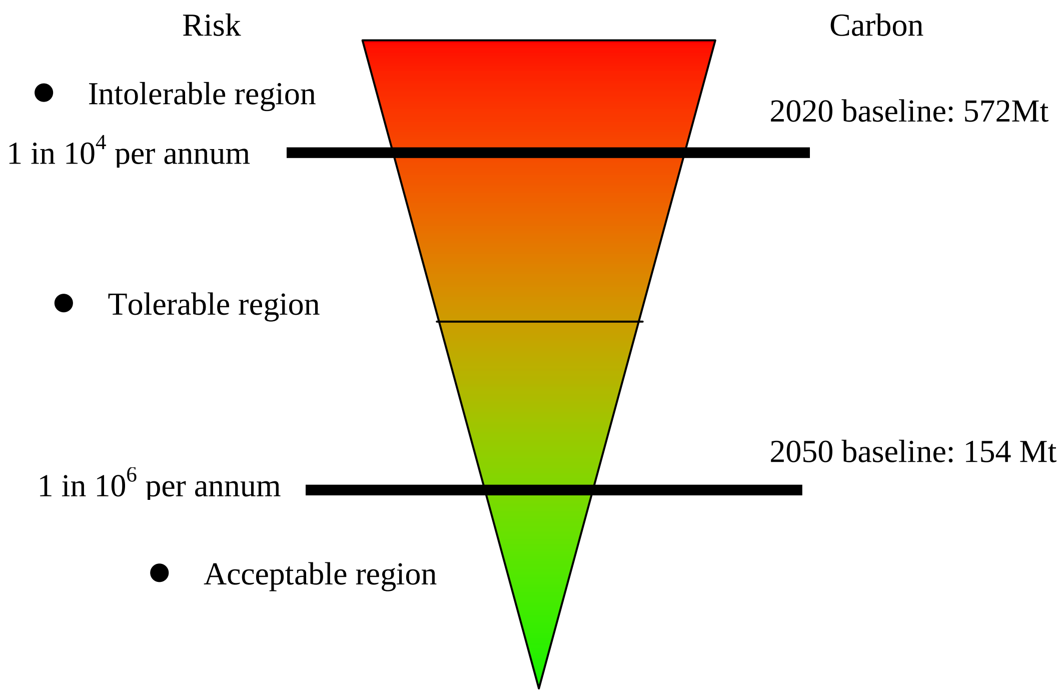

Fig.6.2. Intolerable, tolerable and acceptable regions of risk and carbon footprint

6.2.2 Game theoretical analysis

6.2.2.1 Notations

PF	payoff of the conventional supply chain;
PF'	payoff of the supply chain in the context of Green Supply chain management;
cf_i (i=1,2,3)	carbon footprint of the supply chain at different level ; cf_1 represents the carbon footprint at the acceptable level cf_2 represents the carbon footprint at the tolerable level cf_3 represents the carbon footprint at the intolerable level
R_i (i=1,2,3)	inherent risk of the supply chain contained 'hazardous materials' at different level;

R_1 represents the risk at the acceptable level

R_2 represents the risk at the tolerable level

R_3 represents the risk at the intolerable level

Ct carbon tax;

Cr cost per unit of risk;

6.2.2.2 Payoff function

It is proposed that the manufacturer of 'hazardous' materials within the supply chain is assigned a carbon footprint cf and inherent risk R, as well as a value of PF reflecting the payoff of the conventional supply chain without taking the carbon footprint and risk into account. The payoff function PF' in the context of a green supply chain is expressed as follows:

$$PF' = PF - (R \times Cr) - (cf \times Ct) \tag{6-1}$$

In Equation (6-1), the inherent risk of the supply chain containing 'hazardous materials' can be measured by multiplying the consequence $N(i)$ by the corresponding probability $\Pr ob(i)$ in a particular hazard scenario. The consequence of the hazard in this study is taken as the number of fatalities resulting from environmental accidents or other adverse events attributed to the supply chain, *e.g.* as might occur in the different scenarios (i), *i.e.* process of production, transportation and final disposal.

$$R_i = \Pr ob(i) \times N(i) \tag{6-2}$$

The common approach to measure the carbon footprint is to apply green house gases emission factor multiplied by activity data (DEFRA, 2009). Activity data for a supply chain network mainly reflects the energy consumption in the process of production and transportation, the amount of waste production *etc*.

$$\text{Carbon Footprint (cf)= Estimated Activity Data} \times \text{Emission Factor} \quad (6\text{-}3)$$

The cost per unit public risk reduction (Cr) can be derived from the compensation for fatalities. For example, in the UK 1,000,000 GB pounds (2001 prices) is presented as a value of preventing a fatality (VPF) related to a reduction in risk of one in a hundred thousand (HSE, 2001). Moreover, as there is no specific standard for the cost of carbon emissions, Ct can be employed instead of energy tax in the different scenarios.

If manufacturers do not consider the risk and carbon footprint reduction on the supply chain, the payoff of the total supply chain will not be changed, *i.e.* PF' is equal to PF. However, if manufacturers decide to reduce the risk and carbon footprint within the supply chain, extra costs for supplier selection, technology improvement, equipment upgrading *etc.* may be incurred. On the other hand, the quality and safety of the products can be improved, which may result in additional sales profits. This will be discussed in the following section dealing with the assumptions made for the game theoretical analysis.

6.2.2.3 Assumption for game theoretical analysis

When the current carbon footprint level of the supply chain cf is within the tolerable carbon footprint area (see Fig.6.3), which is higher than the upper limit f_1 of the acceptable carbon footprint area, but lower than the upper limit f_2 of the tolerable carbon footprint area, the manufacturer has two potential strategic choices: either to reduce or to maintain the carbon footprint. Once carbon footprint cf is in the intolerable region as above the f_2 criterion, manufacturers on the supply chain ought to reduce the carbon footprint to the tolerable area at least, if not to the acceptable area. In this approach, assume that the acceptable level should be the 'optimal region' in terms of green supply chain management to minimize the risk and carbon footprint. In addition, the current risk on the supply chain, r_1 and r_2, should correspond to an equivalent carbon footprint, f_1 and f_2, according to the threshold values illustrated in Fig.6.3. For the purpose of analysis, regions 1, 2, 3 are defined as acceptable, tolerable and intolerable regions, respectively.

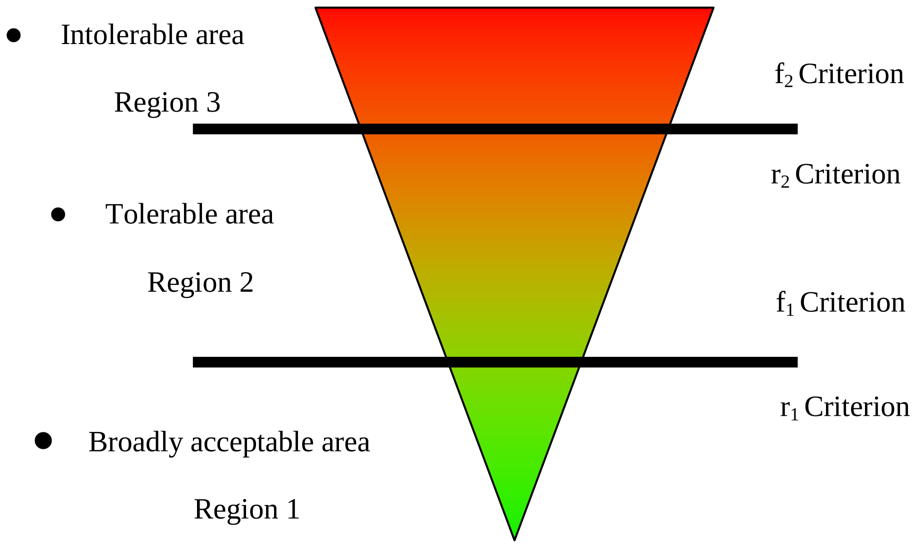

Fig.6.3. Criteria of risk and carbon footprint

It is assumed that additional economic benefits can be generated due to the risk and carbon footprint reduction, and will thus be welcomed by the consumers as 'environmentally friendly'. In Fig.6.4a, let P_{R1}, P_{R2}, P_{R3} denote the yield gaps as a result of the environmental risk decreasing from the tolerable region to the acceptable region, from the intolerable region to the acceptable region and from the intolerable region to the tolerable region, respectively. Similarly, in Fig.6.4b, let P_{cf1}, P_{cf2} and P_{cf3} denote the yield gap as a result of the carbon footprint decreasing from the tolerable region to the acceptable region, from the intolerable region to the acceptable region and from the intolerable region to the tolerable region, respectively.

As shown in Fig.6.4c, let the additional cost of reducing risk from the tolerable level to the acceptable level be ΔC_{R1}, from the intolerable level to the acceptable level be ΔC_{R2}, and from the intolerable level to the tolerable level be ΔC_{R3}. Similarly, in Fig.6.4d, let the additional cost on reducing the carbon footprint from the tolerable to the acceptable level be ΔC_{Cf1}, from the intolerable to the acceptable level be ΔC_{Cf2} , and from the intolerable the tolerable level be ΔC_{Cf3}.

6.2.3 Game scenario one— manufacturers' action

In this scenario, it is assumed that the strategic actions adopted by the manufacturers within the supply chain are the same and simultaneous. According to the above basic payoff function and assumptions, the payoff matrix of manufacturers at different risk or carbon footprint level is given in Table 6.1. Moreover, Table 6.1 can be broken into several sub-tables for the following analysis of manufacturers' strategic actions on improving the current carbon footprint and risk level, but without governmental supervision.

When carbon footprint and risk is at the acceptable level, the manufacturers in the supply chain will not pay more attention to further carbon footprint or risk reduction, as denoted by "($PF - R_1Cr - cf_1Ct$, $PF - R_1Cr - cf_1Ct$)" in Table 6.1.

When both carbon footprint and risk are at the tolerable level (See the payoff matrix in Table 6.2), and if the expected profits P_{R1} and P_{cf1} from the sale of 'environmentally sound' products totally cover the technological innovation cost ΔC_{R1}, ΔC_{cf1} arising from risk and carbon footprint reduction, the following inequalities apply:

$$-\Delta C_{R1} + P_{R1} + r_1Cr > 0 \tag{6-4}$$

$$-\Delta C_{cf1} + P_{cf1} + f_1Ct > 0 \tag{6-5}$$

The dominant strategy is that manufacturers will attempt to reduce both the carbon footprint and risk to the 'acceptable level', as the payoff at acceptable level is higher than that at the tolerable level. Otherwise, manufacturers are reluctant to improve and the situation will remain at the 'tolerable level'.

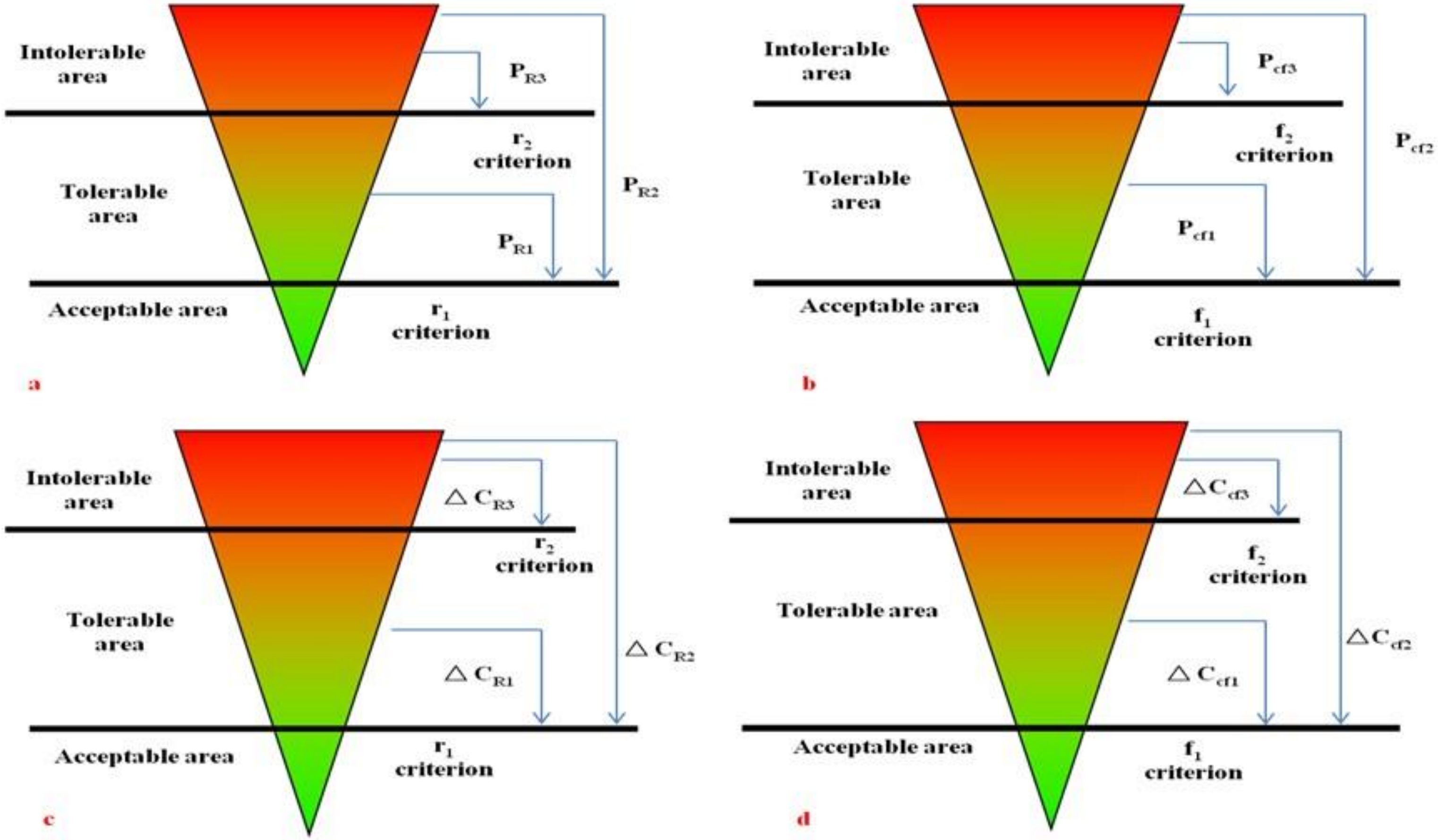

Fig.6.4. Additional profit and cost in different risk or carbon footprint region

Table 6.1 Payoffs of carbon footprint and risk reduction in different regions

Risk / Carbon emissions	Acceptable (r_1)	Tolerable (r_2) ALARP (As Low As Reasonably Practicable)		Intolerable	
Acceptable (f_1)	$(PF-R_1Cr-cf_1Ct,$ $PF-R_1Cr-cf_1Ct)$	Maintain	Reduce to acceptable level	Reduce to acceptable level	Reduce to tolerable level
Tolerable (f_2)	Maintain	$(PF-R_2Cr-cf_2Ct,$ $PF-R_2Cr-cf_2Ct)$	$(PF-(R_2-r_1)Cr-cf_2Ct,$ $PF-(R_2-r_1)Cr-cf_2Ct-\Delta C_{R1}+P_{R1})$	$(PF-cf_2Ct-(R_3-r_1)Cr,$ $PF-(R_3-r_1)Cr-cf_2Ct+P_{R2}-\Delta C_{R2})$	$(PF-cf_2Ct-(R_3-r_2)Cr,$ $PF-(R_3-r_2)Cr-cf_2Ct+P_{R3}-\Delta C_{R3})$
	Reduce to acceptable level	$(PF-R_2Cr-(cf_2-f_1)Ct-\Delta C_{cf1}+P_{cf1},$ $PF-R_2Cr-(cf_2-f_1)Ct)$	$(PF-(R_2-r_1)Cr-(cf_2-f_1)Ct-\Delta C_{cf1}+P_{cf1},$ $PF-(R_2-r_1)Cr-(cf_2-f_1)Ct-\Delta C_{R1}+P_{R1})$	$(PF-(R_3-r_1)Cr-(cf_2-f_1)Ct-\Delta C_{cf1}+P_{cf1},$ $PF-(R_3-r_1)Cr-(cf_2-f_1)Ct-\Delta C_{R2}+P_{R2})$	$(PF-(R_3-r_2)Cr-(cf_2-f_1)Ct-\Delta C_{cf1}+P_{cf1},$ $PF-(R_3-r_2)Cr-(cf_2-f_1)Ct-\Delta C_{R3}+P_{R3})$
Intolerable	Reduce to acceptable level	$(PF-\Delta C_{cf2}+P_{cf2}-(cf_3-f_1)Ct-R_2Cr,$ $PF-R_2Cr-(cf_3-f_1)Ct)$	$(PF-\Delta C_{cf2}+P_{cf2}-(cf_3-f_1)Ct-(R_2-r_1)Cr,$ $PF-(R_2-r_1)Cr-(cf_3-f_1)Ct+P_{R1}-\Delta C_{R1})$	$(PF-\Delta C_{cf2}+P_{cf2}-(cf_3-f_1)Ct-(R_3-r_1)Cr,$ $PF-(R_3-r_1)Cr-(cf_3-f_1)Ct+P_{R2}-\Delta C_{R2})$	$(PF-\Delta C_{cf2}+P_{cf2}-(cf_3-f_1)Ct-(R_3-r_2)Cr,$ $PF-(R_3-r_2)Cr-(cf_3-f_1)Ct+P_{R3}-\Delta C_{R3})$
	Reduce to tolerable level	$(PF-\Delta C_{cf3}+P_{cf3}-(cf_3-f_2)Ct-R_2Cr,$ $PF-R_2Cr-(cf_3-f_2)Ct)$	$(PF-\Delta C_{cf3}+P_{cf3}-(cf_3-f_2)Ct-(R_2-r_1)Cr,$ $PF-(R_2-r_1)Cr-(cf_3-f_2)Ct+P_{R1}-\Delta C_{R1})$	$(PF-\Delta C_{cf3}+P_{cf3}-(cf_3-f_2)Ct-(R_3-r_1)Cr,$ $PF-(R_3-r_1)Cr-(cf_3-f_2)Ct+P_{R2}-\Delta C_{R2})$	$(PF-\Delta C_{cf3}+P_{cf3}-(cf_3-f_2)Ct-(R_3-r_2)Cr,$ $PF-(R_3-r_2)Cr-(cf_3-f_2)Ct+P_{R3}-\Delta C_{R3})$

When the carbon footprint is at the tolerable level, whilst the risk remains intolerable (See Table 6.3), and if the following two inequalities are both satisfied:

$$-\Delta C_{cf1} + P_{cf1} + f_1 Ct > 0 \tag{6-6}$$

$$(r_1 - r_2)Cr + (P_{R2} - P_{R3}) - (\Delta C_{R2} - \Delta C_{R3}) > 0 \tag{6-7}$$

manufacturers will reduce both the carbon footprint and risk to the acceptable level. On the other hand, if the expected profit cannot cover the technological cost of reducing the carbon footprint of products, $(P_{cf1} - \Delta C_{cf1}) + f_1 Ct < 0$, manufacturers will maintain the carbon footprint at the tolerable level, but decrease the risk from the intolerable to the tolerable level, because the expected payoff of risk reduction at the tolerable level is higher than at the acceptable level.

Similarly, when the carbon footprint is at the intolerable level, whilst risk tolerable (See Table 6.4), the dominant strategy for manufacturers is to reduce both the carbon footprint and risk to the acceptable level, as long as the following two inequalities are both satisfied:

$$(f_1 - f_2)Ct + (P_{cf2} - P_{cf3}) - (\Delta C_{cf2} - \Delta C_{cf3}) > 0 \tag{6-8}$$

$$-\Delta C_{R1} + P_{R1} + r_1 Cr > 0 \tag{6-9}$$

Otherwise, manufacturers will maintain the risk at the tolerable level, but decrease the carbon footprint from the intolerable to the tolerable level.

When both carbon footprint and risk are at the intolerable level (See the payoff matrix in Table 6.5), and if both inequalities (6-10) and (6-11) are satisfied, reduction of both carbon footprint and risk to the acceptable level is the dominant strategy for manufacturers, because the economic benefits are greater by taking acceptable action than by taking tolerable action.

$$(f_1 - f_2)Ct + (P_{cf2} - P_{cf3}) - (\Delta C_{cf2} - \Delta C_{cf3}) > 0 \tag{6-10}$$

$$(r_1 - r_2)Cr + (P_{R2} - P_{R3}) - (\Delta C_{R2} - \Delta C_{R3}) > 0 \tag{6-11}$$

According to the above analysis, whether manufacturers are willing to reduce the risk and carbon footprint voluntarily is mainly determined by 'cost-benefit' analysis. If the additional sales profit can cover the technological innovation cost, both risk and carbon footprint will be decreased. Otherwise, manufacturers will keep either the risk or carbon footprint at the original level. In the next section, governmental punitive policy and incentives are involved in the game scenario analysis.

Table 6.2 Payoffs of carbon footprint and risk at tolerable region

Carbon footprint \ Risk		Tolerable (r_2) ALARP (As Low As Reasonably Practicable)	
		Maintain	Reduce to acceptable level
Tolerable (f_2)	Maintain	($PF- R_2Cr-cf_2Ct$, $PF- R_2Cr-cf_2Ct$)	($PF-(R_2-r_1)Cr-cf_2Ct$, $PF-(R_2-r_1)Cr -cf_2Ct-\Delta C_{R1}+P_{R1}$)
	Reduce to acceptable level	($PF-R_2Cr-(cf_2-f_1)Ct-\Delta C_{cf1}+P_{cf1}$, $PF-R_2Cr-(cf_2-f_1)Ct$)	($PF-(R_2-r_1)Cr-(cf_2-f_1)Ct-\Delta C_{cf1}+P_{cf1}$, $PF-(R_2-r_1)Cr-(cf_2-f_1)Ct-\Delta C_{R1}+P_{R1}$)

Table 6.3 Payoffs of carbon footprint at the tolerable region and risk at the intolerable region

Carbon footprint \ Risk		Intolerable	
		Reduce to acceptable level	Reduce to tolerable level
Tolerable (f_2)	Maintain	($PF-cf_2Ct-(R_3-r_1)Cr$, $PF-(R_3-r_1)Cr- cf_2Ct+P_{R2}-\Delta C_{R2}$)	($PF-cf_2Ct-(R_3-r_2)Cr$, $PF-(R_3-r_2)Cr- cf_2Ct+P_{R3}-\Delta C_{R3}$)
	Reduce to acceptable level	($PF-(R_3-r_1)Cr-(cf_2-f_1)Ct-\Delta C_{cf1}+P_{cf1}$, $PF-(R_3-r_1)Cr-(cf_2-f_1)Ct-\Delta C_{R2}+P_{R2}$)	($PF-(R_3-r_2)Cr-(cf_2-f_1)Ct-\Delta C_{cf1}+P_{cf1}$, $PF-(R_3-r_2)Cr-(cf_2-f_1)Ct-\Delta C_{R3}+P_{R3}$)

Table 6.4 Payoffs of carbon footprint at the intolerable region and risk at the tolerable region

Carbon footprint \ Risk		Tolerable (r_2) ALARP (As Low As Reasonably Practicable)	
		Maintain	Reduce to acceptable level
Intolerable	Reduce to acceptable level	$(PF\text{-}\Delta C_{cf2}+P_{cf2}\text{-}(cf_3\text{-}f_1)Ct\text{-}R_2Cr,$ $PF\text{-}R_2Cr\text{-}(cf_3\text{-}f_1)Ct)$	$(PF\text{-}\Delta C_{cf2}+P_{cf2}\text{-}(cf_3\text{-}f_1)Ct\text{-}(R_2\text{-}r_1)Cr,$ $PF\text{-}(R_2\text{-}r_1)Cr\text{-}(cf_3\text{-}f_1)Ct+P_{R1}\text{-}\Delta C_{R1})$
	Reduce to tolerable level	$(PF\text{-}\Delta C_{cf3}+P_{cf3}\text{-}(cf_3\text{-}f_2)Ct\text{-}R_2Cr,$ $PF\text{-}R_2Cr\text{-}(cf_3\text{-}f_2)Ct)$	$(PF\text{-}\Delta C_{cf3}+P_{cf3}\text{-}(cf_3\text{-}f_2)Ct\text{-}(R_2\text{-}r_1)Cr,$ $PF\text{-}(R_2\text{-}r_1)Cr\text{-}(cf_3\text{-}f_2)Ct+P_{R1}\text{-}\Delta C_{R1})$

Table 6.5 Payoffs of carbon footprint and risk at the intolerable region

Carbon footprint \ Risk		Intolerable	
		Reduce to acceptable level	Reduce to tolerable level
Intolerable	Reduce to acceptable level	$(PF\text{-}\Delta C_{cf2}+P_{cf2}\text{-}(cf_3\text{-}f_1)Ct\text{-}(R_3\text{-}r_1)Cr,$ $PF\text{-}(R_3\text{-}r_1)Cr\text{-}(cf_3\text{-}f_1)Ct+P_{R2}\text{-}\Delta C_{R2})$	$(PF\text{-}\Delta C_{cf2}+P_{cf2}\text{-}(cf_3\text{-}f_1)Ct\text{-}(R_3\text{-}r_2)Cr,$ $PF\text{-}(R_3\text{-}r_2)Cr\text{-}(cf_3\text{-}f_1)Ct+P_{R3}\text{-}\Delta C_{R3})$
	Reduce to tolerable level	$(PF\text{-}\Delta C_{cf3}+P_{cf3}\text{-}(cf_3\text{-}f_2)Ct\text{-}(R_3\text{-}r_1)Cr,$ $PF\text{-}(R_3\text{-}r_1)Cr\text{-}(cf_3\text{-}f_2)Ct+P_{R2}\text{-}\Delta C_{R2})$	$(PF\text{-}\Delta C_{cf3}+P_{cf3}\text{-}(cf_3\text{-}f_2)Ct\text{-}(R_3\text{-}r_2)Cr,$ $PF\text{-}(R_3\text{-}r_2)Cr\text{-}(cf_3\text{-}f_2)Ct+P_{R3}\text{-}\Delta C_{R3})$

6.2.4 Game scenario two— governmental sanction

In this game scenario, there are two players who separately represent the government and the manufacturers of potentially 'hazardous materials'. The overall objective of reducing risk and carbon footprint, while still ensuring the economic interest of the supply chain, remains the focal point of the game. In order to simplify the mathematical model, manufacturers will choose the same strategy under the specific government policy, *i.e.* implement production at least within the tolerable region. Let E and U denote the economic benefit that government would gain in terms of revenue when manufacturers produce at the tolerable and intolerable levels, respectively. C_s indicates the cost of governmental supervision. The game between government and manufacturers, when the risk or carbon footprint is at an intolerable level, is shown in Table 6.6. Government makes the decisions between P and NP, which indicates 'Penalty' and 'No-penalty' strategy, respectively. Meanwhile, manufacturers make their own decisions on whether to reduce the risk and carbon footprint to the tolerable level (RT) or to maintain (M) the current carbon footprint and risk level.

This game model contains a three stage game (see Fig.6.5). In the first stage, when there is no penalty from the government (NP), the cost of governmental supervision is higher than the penalties ($C_s > P$). Additionally, the technological cost ($\Delta C_3 = \Delta C_{R3} + \Delta C_{cf3}$) is quite high for manufacturers to bear by reducing both risk and carbon footprint ($r_2 Cr + f_2 Ct + P_3 < \Delta C_3$). Thus, to keep the production mode at the current level (M) is the dominant strategy for the manufacturers.

Table 6.6 Strategic game between government and manufacturers in the intolerable region

Order of payoffs: Government, Manufacturers		Manufacturers	
		RT	M
Government	P	(E-C_S, $PF+(P_{cf3}-\Delta C_{cf3})+(P_{R3}-\Delta C_{R3})-(cf_3-f_2)Ct-(R_3-r_2)Cr$)	(U-C_S+P, $PF-R_3Cr-cf_3Ct-P$)
	NP	(E, $PF+(P_{cf3}-\Delta C_{cf3})+(P_{R3}-\Delta C_{R3})-(cf_3-f_2)Ct-(R_3-r_2)Cr$)	(U, $PF-R_3Cr-cf_3Ct$)

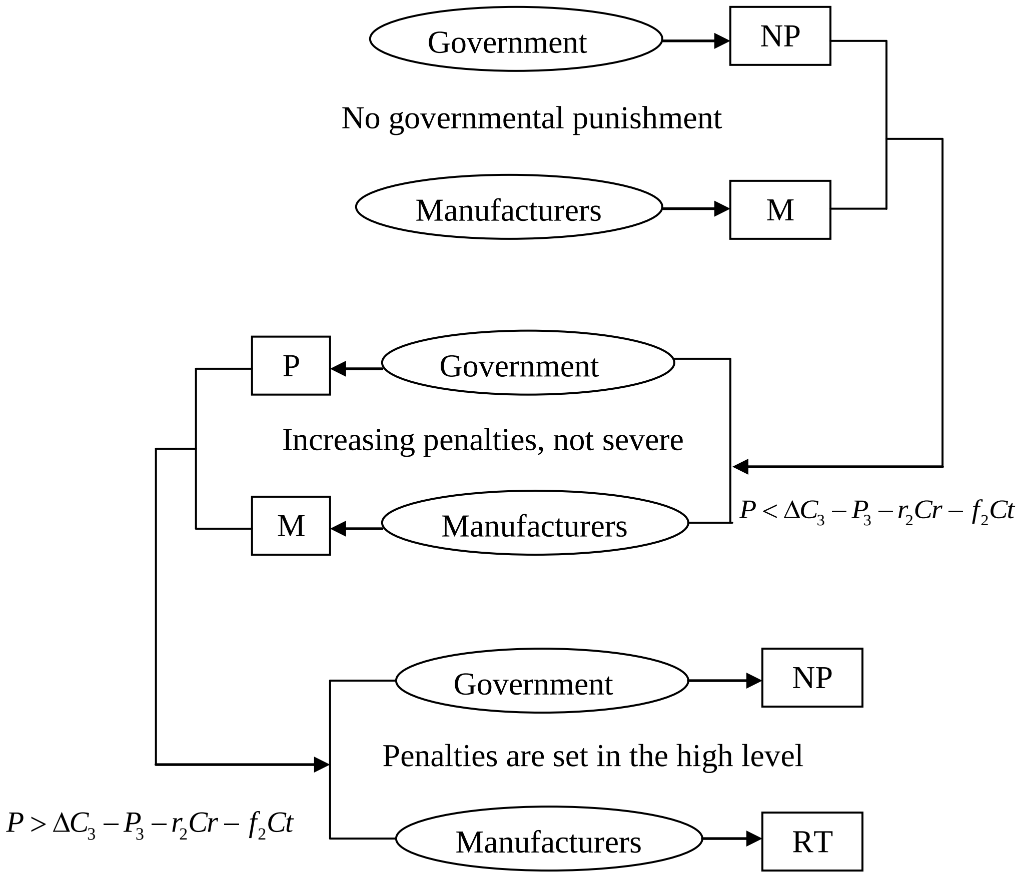

Fig.6.5. Three stages in the punitive game between government and manufacturers

In the second stage, when government decides to penalise (P) the environmentally unfriendly action of manufacturers, and if the economic sanctions are increasing gradually above the supervision cost, as $C_s < P$, manufacturers will prefer paying the economic penalties to maintain the current production mode (M) rather than reducing both the risk and carbon footprint level, since, if the punishment is not severe, the inequality ($r_2Cr + f_2Ct + P_3 + P < \Delta C_3$) applies. Thus, the pair of dominant strategy has been transformed into 'P-M'.

Assuming in the third stage that the governmental penalties are set high enough in terms of the punitive policy, manufacturers will opt to change their existing production mode (RT). The penalties should satisfy the following inequality:

$$P > (\Delta C_{R3} + \Delta C_{cf3}) - (P_{R3} + P_{cf3}) - r_2 Cr - f_2 Ct \quad (6\text{-}12)$$

Moreover, if the technological cost can be totally covered by the additional sales of 'environmentally friendly product', then $r_2 Cr + f_2 Ct + P_3 - \Delta C_3 > 0$, and government will no longer need to take actions to regulate the process (P), manufacturers opting to reduce the risk and carbon footprint to the tolerable level (RT). Thus, the 'win-win' strategy can be 'NP-RT'.

6.2.5 Game scenario three— governmental incentive

In order to promote the supply chain to be much 'cleaner' and 'greener', government should also hold some incentive policies to help the manufacturers upgrade their current production method. Adopting the premise that production is prohibited if either risk or carbon footprint is at the intolerable level, this study only discusses how to incentivize the manufacturers to improve the carbon footprint and risk from tolerable to acceptable level.

Let *I* denote the governmental incentive value in terms of subsidies *i.e.*, through tax breaks, and *V* indicate the additional governmental revenue gained by manufacturers producing at the acceptable level, since manufacturers provide environmentally friendly products for the market. The game between government and manufacturers is a two-stage game, Table 6.7, as depicted in Fig.6.6. Suppose that government initially chooses the strategy I (Incentive) or NI (No Incentive). In response to these options, the manufacturers, in their turn, then have to decide whether to reduce their carbon footprint and risk to the acceptable level (RA) or to maintain at the current level (M).

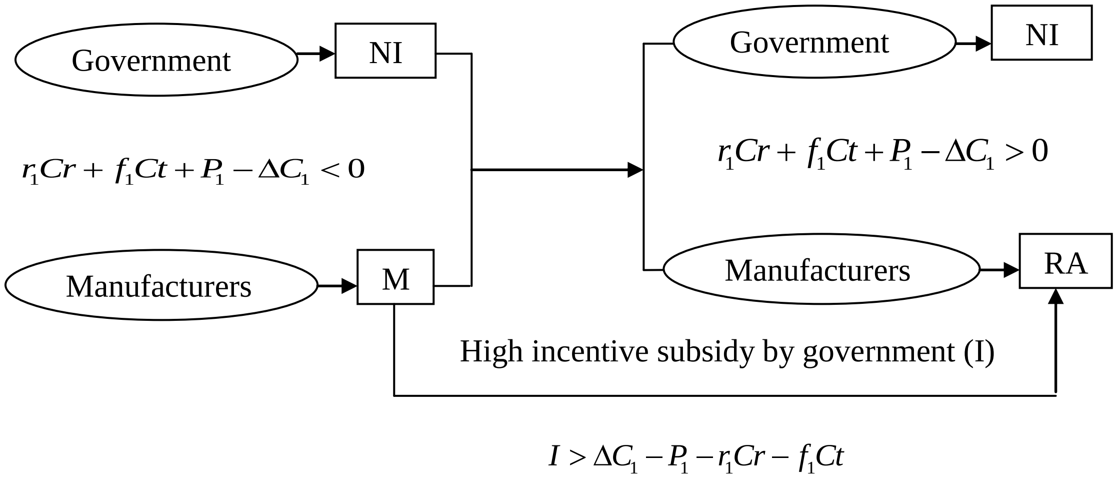

Fig.6.6. Two stages in the incentive game between government and manufacturers

From Table 6.7, to give any subsidy to impel manufacturers to reduce the risk and carbon footprint should be the dominated strategy for government. Thus, government prefers choosing 'NI' rather than 'I'. In the first stage, when government chooses the strategy 'NI', and if $r_1Cr + f_1Ct + (P_{R1} + P_{cf1}) - (\Delta C_{R1} + \Delta C_{cf1}) < 0$, where the technological innovation cost ($\Delta C_1 = \Delta C_{R1} + \Delta C_{cf1}$) cannot totally be covered by the additional sales profits ($P_1 = P_{R1} + P_{cf1}$) and the cost saving resulting from risk and carbon footprint reduction to the acceptable level ($C_s = r_1Cr + f_1Ct$), manufacturers will choose to maintain production in the tolerable region. However, when government chooses to incentivize ('I') the manufacturers to reduce to acceptable level ('RA'), and the incentive subsidy satisfies the following inequality:

$$I > (\Delta C_{R1} + \Delta C_{cf1}) - (P_{R1} + P_{cf1}) - r_1Cr - f_1Ct \qquad (6\text{-}13)$$

manufacturers will tend to reduce risk and carbon footprint from the tolerable level to the acceptable level. Otherwise, if the incentive subsidy is not high enough, manufacturers will choose to maintain current practices.

The second stage suggests that, if $r_1 Cr + f_1 Ct + (P_{R1} + P_{cf1}) - (\Delta C_{R1} + \Delta C_{cf1}) > 0$, where the technological innovation cost can be totally covered, the manufacturers are willing to decrease the risk and carbon footprint to the acceptable level, so that the governmental incentive is not necessary at this stage. Thus, the strategic action pair has been transformed into ('NI-RA'), which is the 'win-win' strategy for both parties.

Table 6.7 Strategic game between government and manufacturers in the tolerable region

Order of payoffs: Government, Manufacturers		Manufacturers	
		RA	M
Government	I	(V-I, $PF+(P_{cf1}-\Delta C_{cf1})+(P_{R1}-\Delta C_{R1})-(cf_2-f_1)Ct-(R_2-r_1)Cr+I$)	($-I$, $PF-R_2Cr-cf_2Ct$)
	NI	(V, $PF+(P_{cf1}-\Delta C_{cf1})+(P_{R1}-\Delta C_{R1})-(cf_2-f_1)Ct-(R_2-r_1)Cr$)	(0, $PF-R_2Cr-cf_2Ct$)

6.2.6 Case example

In order to show how game theory informs the national manufacturers and government to reduce risk and carbon footprint, a case example is presented in this section. Here, the data are mainly sourced from the annual reports of Tesco Group (2007-2011) and the corporate responsibility report (2010). To demonstrate the manufacturers' action without governmental supervision, we assume that the risk is initially at the tolerable level within the current supply chain, whilst the carbon footprint remains intolerable. Table 6.8 shows the game model parameters selected for the case example. Thus, the payoffs matrix shown in Table 6.4 can be quantified. Moreover, a game theory tool based upon Visual Basic programming is designed to solve the two persons pure and mix-strategy game, where the quantified payoffs matrix can be seen in Fig.6.7. The solution suggests a dominant strategy in this game, that the carbon footprint should be reduced to the acceptable level, whilst the risk still remains at the tolerable level. The dominant strategy is greatly affected by the purchase preference of customers who select environmentally friendly products. If the customers prefer environmentally friendly products more than existing products, the demands of the green products should be increased such that the carbon footprint is reduced, and thus to improve the carbon footprint level. For instance, Tesco group has surveyed that 59% of UK customers bought at least one carbon labelled product (Tesco, 2011). However, the current cost paid for risk reduction is considered about three times larger than the benefit (HSE, 2001), which highlights the difficulty of reducing the environmental risk at the same time.

Table 6.8 Model parameters of the case examples

Parameters	Numerical value	Source
PF	60931 million GB Pounds	Tesco Group revenue at 2010 (exc.VAT)
cf_3	5.44 million tonnes	The carbon footprint measured by the Tesco Group at 2011.
f_1	0 tonne	Tesco has claimed to be a 'zero-carbon' business by 2050.
f_2	3.81 million tonnes	As the carbon emissions of the products in the Tesco supply chain is claimed to be reduced by 30% at 2020, f_2 can be derived by the current carbon footprint (5.44 million tonnes) to multiply 70%
Cr	10^6 GB pounds	A value of preventing a fatality (VPF) related to a reduction in risk of one in a hundred thousand
Ct	£ 12/tonne CO_2	The Carbon Trust (2010) suggests that the carbon price is fixed as £ 12/tonne
R_2	10^{-5}	Assume the risk is at the tolerable level
r_1	10^{-6}	The risk criterion between tolerable and acceptable region
ΔC_{cf3}	22.08 million GB pounds	Tesco has launched the green clubcard program, worth over £ 10 million to incentivize green behaviour of the consumers each year, which subordinates to the indicator 'group cost of sales'. Thus, the average growth rate of cost of sales is roughly calculated as 9.2%. The cost for carbon footprint reduction to year 2020 can be measured as $10\times(1+9.2\%)^9=22.08$ million GB pounds, whilst selecting year 2011 as the baseline.
ΔC_{cf2}	309.52 million GB pounds	The cost of 2011 is still used as the baseline, the cost for carbon footprint reduction to the year 2050 can be measured as $10\times(1+9.2\%)^{39}=309.52$ million GB pounds
P_{cf3}	185.36 million GB pounds	Tesco has carbon labeled 1100 products since 2008, which account for 1.3 billion of sales each year. As the group operating profit margin is 6.3% at 2011, it is suggested that the 'green' products profit is $1300\times6.3\%=81.9$ million pounds in 2011. In addition, we have calculated the average growth rate of the sales profit as 9.5%. Thus, sales profit at year 2020 can be measured as $81.9\times(1+9.5\%)^9=185.36$ million GB pounds, whilst selecting year 2011 as the baseline.
P_{cf2}	2821.20 million GB pounds	Sales profit at year 2020 can be measured as $81.9\times(1+9.5\%)^{39}=2821.20$ million GB pounds.
ΔC_{R1}	6411.32 million GB pounds	The risk is managed as a key issue in the Tesco group, it is suggested that the annual administrative expense to be fully used for risk control. HSE (2001) suggests the cost discount rate is suggested by 3.5% for risk reduction. Thus, the cost for risk reducing from the tolerable to the acceptable level can be measured as $1676\times(1+3.5\%)^{39}=6411.32$ million pounds, whilst selecting year 2011 as the baseline.
P_{R1}	2137.11 million GB pounds	HSE suggests the cost is three times larger than the benefits, when applying risk to workers. Thus, the benefit for risk reducing from the tolerable to the acceptable level can be measured as $6411.32/3=2137.11$ million pounds.

Fig.6.7. Solution of case example in the designed game theory tool

6.3 Strategic options

Based upon the above game theoretical analysis, the potential actions of manufacturers within the different scenarios are summarized as followed. When there is no supervision from the government, the dominant strategy of the manufacturers will mainly depend on the difference between the payoff of the re-designed supply chain and the payoff when carbon footprint and risk are reduced to the specified level, *e.g.*, tolerable level, acceptable level. If the profit is shown to be more than the cost following a reduction of the carbon footprint or risk through the whole supply chain, the strategy that manufacturers are expected to adopt is to implement improvements to production methods. Otherwise, the strategy is to keep the original risk and carbon footprint level.

The preferential purchase of environmentally friendly products by customers will greatly influence the dominant strategies of manufacturers when there is no supervision from the government. However, when the government increases the penalties on the environmental unfriendly actions of manufacturers, the strategic choices of the manufacturers will be decided by the level of such penalties. If the punishment is slight, and it is not large enough to induce the manufacturers to change the current risk and carbon footprint level, the dominant strategy is to retain the current level. If the sanction is large enough, improving the risk and carbon footprint to the tolerable level at least should be the dominant strategy for manufacturers. In conclusion, when the government instigates a sanctions policy for the environmentally unfriendly actions of the manufacturers, the result will tend towards the risk and carbon footprint level situated within the tolerable band at best.

If the government aims to further improve the risk and carbon footprint to the broadly acceptable level, then an incentive policy will be required, such as a subsidy from government which may promote the risk and carbon footprint reduction.

6.4 Summary

This Chapter provides a novel approach in the context of green supply chain management, using game theory to analyze the strategies selected by the manufacturers of ‘hazardous’ materials, to reduce environmental risk and the associated carbon footprint. Through the application of the ‘tolerability of risk’ concept, different judgments about the extent of environmental risk and carbon footprint reduction have been determined. Currently, scant attention is given to ‘holistic’ supervision of the supply chain of hazardous materials by governments, and thus the starting hypothesis here is that the default strategy that manufacturers will adopt is to improve their carbon footprint and level of environmental risk, according to a perceived consumer preference for environmental friendly products, with the aim of increasing revenue. Moreover, it is assumed that, once necessary governmental policy has been established in the supply chain management of hazardous materials, the strategic choices of the manufacturers should be influenced by government penalties or incentives. Here, the application of game theory provides a useful insight. Chapter 7 uses the principle of dynamic optimisation technique to discuss the maximum extent of the environmental risk and associated carbon footprint reduction, as well as to minimize the total economic cost on the supply chain, based upon the above game theoretical analysis.

Chapter 7: An Optimisation Model for Supply Chain

7.1 Introduction

The increasing demand for consumption has greatly accelerated the depletion of resources and therefore leads to environmental problems. The supply chain is no exception. Confronted with balancing profits and the environmental performance, the new consideration arouses management for supply chain which may be known as "Green Supply Chain Management" (GrSCM) (Sheu, Chou and Hu, 2005). Green supply chain management can be defined as a series of regulations and policies for supply chain management in the context of sustainable development, with particular attention to minimizing the environmental impact from the suppliers to the end users (Basu and Wright, 2008). In contrast to conventional supply chain management, the strategy that is adopted by green supply chain management is a "win-win" strategy in effect. Through its application, not only the business profits can be increased, but also environmental benefits can be generated (Zhu and Cote, 2004). Furthermore, green supply chain management mainly focuses on waste reduction within the industrial system, while lessening the material consumption, saving energy, preventing hazardous materials stream into the environment (Ho, 2009). This chapter considers how to re-design the conventional supply chain network of 'hazardous' materials in a more sustainable way and thus building a dynamic optimisation model, not only to minimize the total economic cost, but also the inherent risk and carbon footprint throughout the process of supply chain. In particular, followed by extending the responsibility of supply chain, the inherent risk and carbon footprint in various scenarios, such as production, transportation and final disposal, are taken into account for the model construction.

7.2 Basis of dynamic optimisation

Dynamic optimisation can be understood as 'dynamic programming', from which a sequential or multistage decision progress can be solved by transforming it into a single stage optimisation problem (Bellman, 1957). Fig.7.1 shows a typical process of dynamic optimisation, composed of a series of sub-optimisation problems, which interact with each other, *i.e.* the output of one stage could be the input to the next (Willis and Finney, 2003).

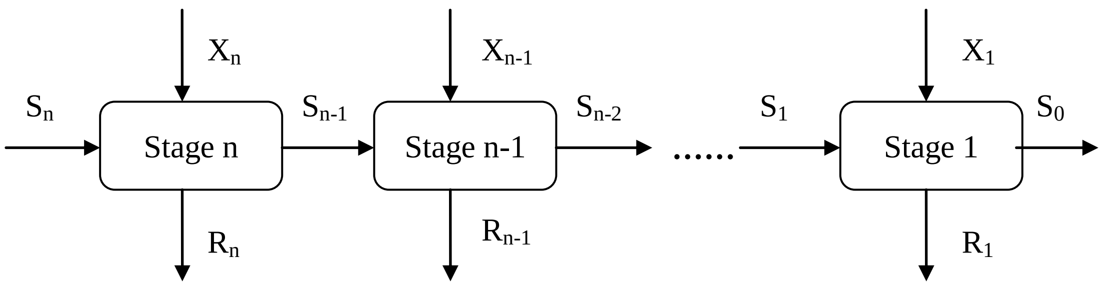

Fig.7.1. Typical process of dynamic optimisation

(adopted from: Willis and Finney, 2003)

From Fig.7.1, X_n is the decision variable, whilst S_n is the input variable at stage n, and the corresponding output variable S_{n-1} can be expressed as followed:

$$S_{n-1} = T(S_n, X_n) \tag{7-1}$$

where T indicates a transformation process of the state variable. Meanwhile, there is a return function R_n of the input and output state variables, shown in Equation (7-2).

$$R_n = R_n(S_n, S_{n-1}, X_n) \tag{7-2}$$

Thus, the dynamic optimisation is to maximise the n stage return function. Assuming $f_n(S_n)$ is the optimal return function with given the system in state S_n, and a system objective g, which can be expressed as followed:

$$f_n(S_n) = \max_{X_1,\cdots,X_n} g[R_n(S_n, X_n), R_{n-1}(S_{n-1}, X_{n-1})\cdots R_1(S_1, X_1)] \tag{7-3}$$

subject to the Equation (7-1) as the constraint condition.

The above Equation (7-3) can be decomposed by n sub-optimisation problems, by means of calculating the optimal return function at each stage. In this premise, the total return from stage 1 to n can be separated as followed:

$$g[R_n(S_n, X_n),\cdots, R_1(S_1, X_1)] = g_1[R_n(S_n, X_n), g_2(R_{n-1}(S_{n-1}, X_{n-1})\cdots, R_1(S_1, X_1))] \tag{7-4}$$

where g_1 and g_2 are the real-valued functions. Based upon the Equations (7-3) and (7-4), the optimal return function can be transformed as followed (Nemhauser, 1966):

$$f_n(S_n) = \max_{X_1,\cdots X_n} g_1[R_n(S_n, X_n), \max_{X_1,\cdots X_n} g_2(R_{n-1}(S_{n-1}, X_{n-1})\cdots R_1(S_1, X_1))] \tag{7-5}$$

As the returns are addictive, Equation (7-5) can be transformed again, shown below:

$$f_n(S_n) = \max_{X_n}[R_n(S_n, X_n) + f_{n-1}(S_{n-1})] \tag{7-6}$$

Thus, Equation (7-6) can be seen as the general mathematical expression of dynamic programming, which seeks to optimize the remaining decisions in terms of the state resulting from the first decisions.

The following section will invoke the basis of the dynamic optimization technique to build a specific model applicable to supply chain networks to reduce the inherent risk, carbon footprint and the associated additional cost.

7.3 Optimisation model

The starting point of dynamic optimisation is to find out the possible stages of optimisation. In this study, there are two stages of optimisation, shown in Fig.7.2. In the first stage, the optimisation model is built to maximize the reduction extent of inherent risk and carbon footprint on the whole supply chain. Once the maximum reduction extent has been determined, an optimization model to minimize the total economic cost is established in the second stage. Moreover, a full lifecycle perspective has been incorporated into the supply chain model, including production, transportation and disposal.

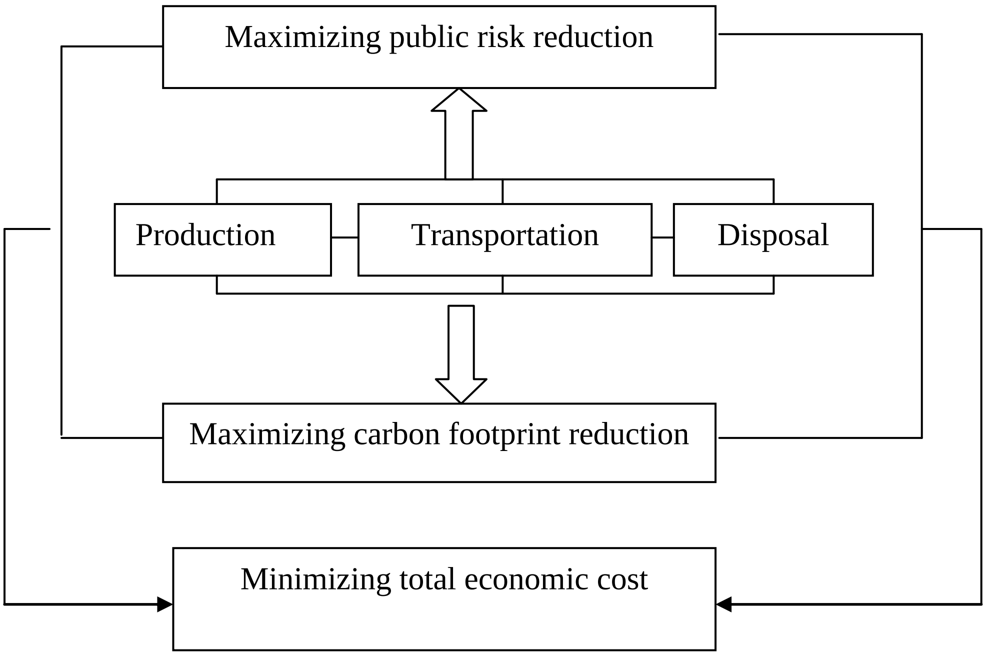

Fig.7.2. Flow-process of dynamic optimisation model

7.3.1 Maximizing the environmental risk reduction

The risk to the environment resulting from the complete supply chain involving 'hazardous' materials, is deemed as the risk which will result in casualties to people, and thus give rise to fatalities in the context of the product life-cycle. There are three important scenarios incorporated into the supply chain inherent risk calculation, which are production, delivery, waste disposal, respectively. Accordingly, the risk decrement of these three scenarios can be denoted as ΔR_p, ΔR_t and ΔR_d. Therefore, the annual reduction of the inherent risk on the supply chain network can be expressed as following:

$$\Delta R = \Delta R_p + \Delta R_t + \Delta R_d \tag{7-7}$$

As discussed in the Chapter 6, the inherent risk can be measured by multiplying the consequence N by the corresponding probability Prob in a particular hazard scenario (Faisal and Mahmoud, 2003).

$$Risk = \Pr ob \times N \tag{7-8}$$

The consequence of a hazard scenario in this study, is taken as the number of fatalities resulting from environmental accidents or other adverse events attributed to the supply chain, *e.g.* as might occur in the different scenarios, process of production, transportation and final disposal. Assuming that inherent risk has not previously been considered by the conventional supply chain network, consequently its reduction can be derived as followed:

$$\Delta R = R - 0 = \Pr ob_p \times N_p + \Pr ob_t \times N_t + \Pr ob_d \times N_d \tag{7-9}$$

where $\Pr ob_p$, $\Pr ob_t$ and $\Pr ob_d$ indicate the annual probability of the hazard events in the process of production, transportation, disposal respectively, with the corresponding annual fatalities N_p, N_t and N_d caused by these hazard scenarios.

According to the framework of "Tolerability of risk" (See the section 6.2.1), the annual probability of the hazard can be determined, and thus the number of fatalities at different hazard scenarios are converted into decision variables. Thus, the optimization model to maximize public risk reduction is built as following:

$$\max \Delta R = \Pr ob_p \times N_p + \Pr ob_t \times N_b + \Pr ob_d \times N_d$$
$$s.t. \begin{cases} N_p \le a \\ N_t \le b \\ N_d \le c \\ N_p + N_t + N_d \le d \end{cases} \tag{7-10}$$

where a, b, c and d are the constant representing the annual fatalities in terms of the criteria suggested by the principle of 'tolerability of risk'.

7.3.2 Maximizing the carbon footprint reduction

Carbon footprint is regarded as a new indicator, which has been widely adopted as "*the total set of greenhouse gas emissions caused directly and indirectly by a person, organization, event or product*" (Carbon Trust, 2009). In the supply chain network, carbon footprints are produced in every stage, from product manufacturing, delivery and to the final disposal.

Let ΔCF denote the total annual reduction of the carbon emissions in the whole supply chain network. Specifically, ΔCF_P, ΔCF_t and ΔCF_d indicate the carbon footprint reduction at the production, transportation and disposal stages, respectively.

$$\Delta CF = \Delta CF_p + \Delta CF_t + \Delta CF_d \tag{7-11}$$

As noted in the Chapter 6, the common approach to estimate the carbon footprint is to apply green house gases emission factor multiplying activity data (DEFRA, 2009). Activity data for a supply chain network mainly reflects the activities in the process of production, transportation, waste disposal, which may generate greenhouse gases emissions.

$$\text{Carbon Footprint (cf)} = \text{Estimated Activity Data} \times \text{Emission Factor} \tag{7-12}$$

Assuming that carbon footprint still has not been considered by the conventional supply chain network, the reduction of carbon footprint can be derived as followed:

$$\Delta CF = \sum_i A_{pi} G_{pi} + \sum_j B_{tj} G_{tj} + \sum_k C_{dk} G_{dk} \tag{7-13}$$

where A_{pi} denotes the ith activity contributed to annual carbon emissions in the process of production, *e.g.* various energy consumption (burning oil, coal, compressed natural gas *etc*). Similarly, B_{tj} indicates the annual transportation distances according to jth vehicle, and C_{dk} is the annual volume of kth waste material generation, *e.g.* paper, plastic, glass *etc*. G_{pi}, G_{tj} and G_{dk} indicate the corresponding greenhouse emission factor at the predetermined scenarios, production, transportation and disposal, separately. In order to calculate the carbon footprint conveniently, as well as simplify the computation complexity, this approach has been embodied into a decision support tool based upon

Visual Basic Programming, shown in Fig.7.3, by taking the carbon footprint calculation in the process of production as an example. Moreover, the details of carbon footprint calculation in the scenarios of production, transportation and disposal can be found in the Appendix A-User manual for decision support tool.

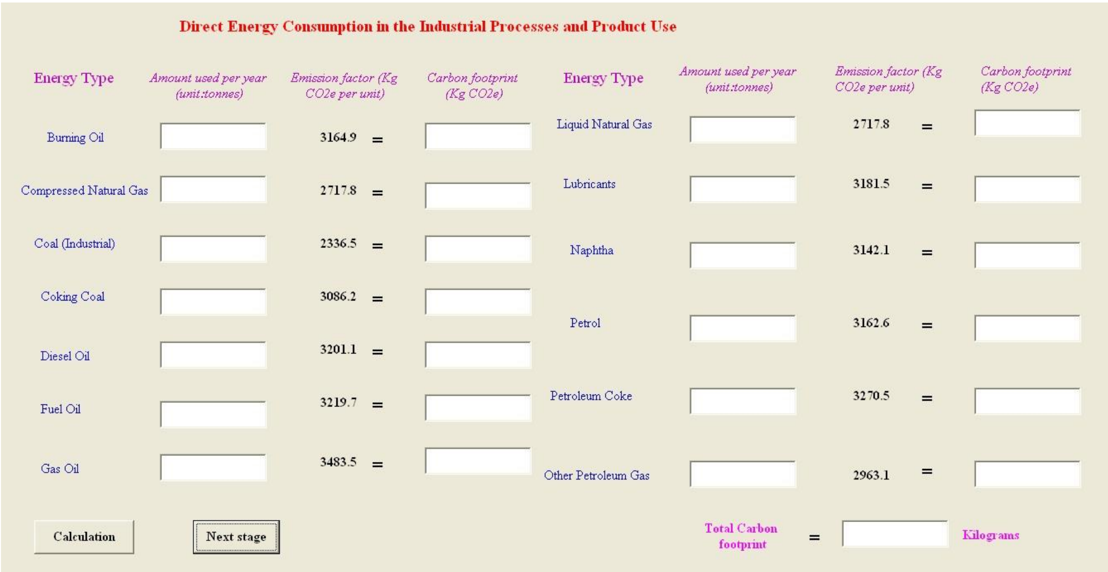

Fig.7.3. Screenshot of the carbon footprint calculation in the industrial process

As the greenhouse emission factors G_{pi}, G_{tj} and G_{dk} can be assumed to be constant, the optimization model to maximize total carbon footprint reduction is built as follows:

$$\max \Delta CF = \sum_i A_{pi} G_{pi} + \sum_j B_{tj} G_{tj} + \sum_k C_{dk} G_{dk}$$

$$s.t. \begin{cases} A_{pi} \le e \\ B_{tj} \le f \\ C_{dk} \le h \end{cases}$$

(7-14)

In the above optimization model, the constrained conditions are derived from the strategy for carbon footprint reduction of the specific organisation, *i.e.* each manufacturer on the supply chain network should predetermine annual energy consumption for their production (e being represented as a constant), annual delivery distances (f being represented as a constant), as well as annual waste generation (h being represented as a constant).

7.3.3 Minimizing the additional cost

As the environmental policy for the conventional supply chain network usually focuses on the production process as well as the delivery of the product to the market and the consumer, the management measures still have not laid sufficient stress on reducing the consumption of 'hazardous' materials. Especially the treatment and disposal of hazardous materials is usually given little deliberation in the post-consuming stage, even though the amount of waste materials has increased over the past few decades (Zhu and Cote, 2004). In this study, the total additional cost, in the context of green supply chain network, should be minimized by not only the cost for production, delivery and waste materials disposal, but also the cost for reducing the inherent risk and carbon footprint. Thus, the total annual additional economic cost $\Delta C_{additon}$ can be expressed as follows:

$$\Delta C_{addition} = \Delta C_p + \Delta C_t + \Delta C_d - \Delta C_R - \Delta C_{CF} \quad (7\text{-}15)$$

where ΔC_p, ΔC_t and ΔC_d denote the annual increased cost for production, transportation and waste materials disposal respectively. These additional costs generated by various stages of the supply chain, can reflect the efforts paid to risk and carbon footprint reduction by organizations, for instance including such measures as equipment replacement, technical renovation for raw materials selection, packaging *etc.*, in the process of production, vehicles inspection and repairing in terms of transportation, promoting the waste materials recycle and reuse *etc*. On the contrary, ΔC_R and ΔC_{CF}

denote annual saved cost since the risk and carbon footprint will have been reduced, which can be expressed in the following equations.

$$\Delta C_R = \Delta R \times Cost(R) \tag{7-16}$$

$$\Delta C_{CF} = \Delta CF \times Cost(CF) \tag{7-17}$$

where $Cost(R)$ indicates as the cost that per unit of risk reduction. Similarly, $Cost(CF)$ indicates the cost that per unit of carbon footprint reduction. In this study, carbon tax is suggested measuring the cost of carbon footprint reduction. Thus, the objective function of additional cost, as equation (7-15) can be transformed as followed:

$$\Delta C_{addition} = \Delta C_p + \Delta C_t + \Delta C_d - \Delta R \times Cost(R) - \Delta CF \times Cost(CF) \tag{7-18}$$

Let $\Delta C_p, \Delta C_t, \Delta C_d$ be the constant as the related data which can be derived from the annual financial report of the specific organizations. The maximum extent of risk and carbon footprint reduction, ΔC_R and ΔC_{CF} can be derived from the expressions (7-10) and (7-14). Therefore, the optimization model for minimizing the total economic cost is only determined by the decision variables $Cost(R)$ and $Cost(CF)$, which is built as following:

$$\min \Delta C_{addition} = \Delta C_p + \Delta C_t + \Delta C_d - \Delta R \times Cost(R) - \Delta CF \times Cost(CF)$$
$$s.t \begin{cases} Cost(R) \le m \\ Cost(CF) \le n \\ \Delta R \times Cost(R) < \Delta C_p + \Delta C_t + \Delta C_d \\ \Delta CF \times Cost(CF) < \Delta C_p + \Delta C_t + \Delta C_d \end{cases} \tag{7-19}$$

7.4 An illustrative example

In this Section, an example is given to illustrate how the above dynamic optimization model works. However, this is just an example to demonstrate the merit of the approach. It should be acknowledged that the real situation could be much more complex.

UK Health and Safety Executive (HSE) suggest the probability of any large-scale industrial hazard *e.g.* explosion, poisonous gas leakage *etc.*, are nearly the same in a certain time period, which is 1 in 10^4 as the maximum frequency within tolerable risk region to any public member (HSE, 1988). Moreover, assume that every organization in the supply chain should control the number of fatalities below 50 during the process of production, transportation and disposal, based on the HSE guidance (HSE, 2005). Thus, the optimization result can be derived by means of LINGO programming (LINDO Systems), shown in Table 7.1.

Table 7.1 Maximum reduction of public risk

Parameters	Constraint conditions	Maximum objective value
$\Pr ob_p = 10^{-4}$ $\Pr ob_t = 10^{-4}$ $\Pr ob_d = 10^{-4}$	$N_p \le 20$ $N_t \le 20$ $N_d \le 20$ $N_p + N_t + N_d \le 50$	$\Delta R = 0.005$

With regard to the optimization of the carbon footprint reduction, the supply chain of croissants is selected in the illustrative example (Carbon Trust, 2008). Table 7.2 reflects the corresponding greenhouse emission factors, constraint conditions and the maximum objective value. Here, the calculated maximum objective value in Table 7.2 indicates the carbon footprint per tonne of croissants. Assume that ten thousand tonne of croissants have been produced in this example. Thus, the total annual maximum carbon footprints are measured as 16900 tonnes. Once the maximum reduction of public risk and carbon footprint has been determined, the optimum result to minimize additional cost can be solved by the expression (7-19).

Table 7.2 Maximum reduction of carbon footprint

Parameters	Constraint conditions	Maximum objective value
$G_{electricity} = 0.5 kg / kwh$ $G_{gas} = 0.2 kg / kwh$ $G_{delivery} = 1 kg / km$ $G_{waste-transport} = 2 kg / km$ $G_{waste} = 800 kg / tonne$	$A_{electricity} \le 300 kwh$ $A_{gas} \le 1000 kwh$ $B_{delivery} \le 640 km$ $C_{waste-transport} \le 150 km$ $C_{waste} \le 0.5 tonnes$	$\Delta CF = 1690 kg$

The detailed preferences are shown in Table 7.3, from which it is supposed the croissants factory spends a million pounds annually for business development. The Cost of per unit risk reduction $Cost(R)$ is derived from the monetary value for per fatalities in terms of the UK regulation (HSE, 2003). Moreover, as there is no specific standard for the cost of carbon emissions in UK, cost of per unit carbon footprint reduction $Cost(CF)$ is suggested by EU Committee as carbon tax (€4 to €30 per tonne) and has been converted into British Pounds by yearly average official exchanging rate (Kanter, 2010).

Table 7.3 Minimum total economic cost

Parameters	Constraint conditions	Minimum objective value
$\Delta C_p + \Delta C_t + \Delta C_d = 10^6$	$Cost(R) \le 1,336,800$ $3 \le Cost(CF) \le 25$	$\Delta C_{addition} = 570,816$

7.5 Summary

This Chapter provides insight to formulate a dynamic optimization approach to increase performance along the three dimensions of the Triple Bottom Line (Economic, Social and Environment), whilst minimizing public risk, carbon footprint and economic cost in the context of green supply chain management. There are two stages of the built optimisation model. Maximizing the reduction extent of inherent risk and carbon footprint on the whole supply chain should be considered at the first stage. Consequentially, minimizing the total economic cost is implemented at the second stage, based upon the maximum reduction extent of risk and carbon footprint. A case example is provided, by using the croissants factory to illustrate how the dynamic optimisation model works.

As 'hazardous' materials are defined in the Introduction of this study, which may cause a risk or damage to the environment especially once the 'hazardous' materials have been converted to the hazardous waste materials. Thus, careful materials selection is becoming an increasingly important aspect of product design to promote cleaner production and improve the quality of products for public consumption. Subsequently, Chapter 8 describes an environmental evaluation approach to aid decision-making on materials selection in the context of cleaner production.

Chapter 8: An Environmental Evaluation Approach for Materials Selection[4]

8.1 Introduction

Materials selection can be done in different ways, but the principles are quite similar. Generally, selection of materials for products is either 'design oriented', driven by functional demands, requiring substantial consideration of mechanical, physical and chemical properties (Edwards, 1994; Ashby, 2005; Kalpakjian and Schmid, 2006) 'product oriented' by market or public demand (Ljungberg and Edwards, 2003), or 'cost oriented' aiming at manufacturing cost reduction (Farag and Magd, 1992). In recent years, the concept of 'green' and 'low-carbon' technology has been gradually entering into product lifecycle management, both as a measure against 'climate change' and for sustainability. Simultaneously, the concept of "environmental conscious design" has gradually emerged in manufacturing, in particular focusing on "design for environment" (Zhang, Kuo, Lu and Huang, 1997; Fiksel, 2009). From the perspective of the 'Hierarchy of Waste', the most preferable strategy for encompassing sustainable development is to prevent or eliminate waste (DEFRA, 2007). The mitigation of the adverse impact of products on the environment and human health can be achieved in part by the careful selection of raw materials, thus improving product lifecycle (including reusability and recyclability), reforming the quality of products and minimizing the amount and toxicity of waste generated during manufacturing processes *etc*. (Tchobanoglous and Kreith, 2002; Williams, 2005). In this context, environmental consideration is an increasingly important component in materials selection, in order to

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[4] This chapter has been published by the Journal "Materials & Design". See details in: Zhao, R., Neighbour, G., Deutz, P., McGuire, M., 2012. Materials Selection for Cleaner Production: An Environmental Evaluation Approach. *Materials & Design* 37, 429-434.

adapt product design to promote cleaner production, provide sustainable products for public consumption and achieve long term commercial success.

This Chapter presents a convenient approach, using a 'binary-dominance matrix' integrated with grey relational analysis, for application by engineers to aid decision-making on materials selection, whilst taking environmental factors into account. Grey relational analysis is a quantitative method used to aid decision making, by examining how closely the value of each attribute approaches to value of the ideal parameter (Liu and Lin, 2006). This integrated methodology is described in detail in the following Section 8.2. A computational tool, based on a spreadsheet calculation, has also been devised to help engineers and designers better understand and employ this approach. Moreover, this work mainly focuses on selection between similar materials (including type and composition) to further improve the environmental performance of the product. A study to select a range of poly(vinyl chloride) (PVC) materials for handbag manufacturing is used as a case example.

8.2 Methodology

8.2.1 Evaluation indicator selection

The evaluation approach starts from the selection of necessary indicators for cleaner production. The use of environmental and economic evaluation indicators is an efficient way to help improve and monitor the processes of product design. Following the basic principles and guidelines of 'design for environment' (Tscoulfas and Pappis, 2008, Fiksel, 2009, Allione, 2011), this study has identified a number of typical indicators which best represent environmental impact, *e.g.* on human health risk / toxicity, economics and resource efficiency, as a basis for materials selection. These indicators listed in Table 8.1 are generic in the context of 'sustainable development', but, in order to distinguish their importance, weighting value need to be assigned to them. This is discussed below.

Table 8.1 Selection of environmental criteria

Indicators
Energy consumption
Human health risk / toxicity
Materials recyclability
Materials reusability
Use of recycled materials
Manufacture defects
Defects recyclability
By-products
By-products recyclability
Waste production
Manufacture cost
Sales profit

8.2.2 Determination of weighting factors

As the selected evaluation criteria are not equally important relative to each other and highly dependent on the product, it is necessary to introduce some form of weighting as part of the evaluation process. Generally, there are two common approaches for determining the extent of weighting required: objective and subjective. The former is mainly based upon the data of the attributes, *e.g.* the entropy approach, while the latter is based on the decision maker's preferences, *e.g.* the analytic hierarchy process (AHP) (Shanian and Savadogo, 2006; Rao and Davim, 2008; Rao and Patel, 2010). The 'Binary-dominance matrix' method is a simplified way of applying the subjective weighting approach, and has been employed in this study, in order to reduce the computational time and complexity (Hurst, 1999).

In this approach, all the criteria are listed on both vertical and horizontal axes of a matrix, and then the numerical value 1 or 0 is input into each box generated by the intersection of the axes according to their relative importance. Each individual criterion is evaluated separately against every other criterion. If a pair of indicators is judged as equal in importance, a value of 0.5 is assigned to each. Once all the indicators have been scored by 0, 1 or 0.5, each row of the matrix should be increased by 1 to ensure the arithmetic validity. Thus, the weight value can be derived as the result of the aggregated score of each indicator divided by the total score of all the indicators, as shown in the Equation (8-1).

$$W = \frac{x_i + 1}{\sum_{i=1}^{n}(x_i) + 1} \qquad (8\text{-}1)$$

where W is the weighting, x_i is the score of the individual criterion.

The weight value can be determined from different case studies. However, as a simplified approach, the criteria in Table 8.1 will be examined by comparing search results from an online science database, which reflects the current academic research interests or attentions paid to environmental or sustainable studies. Scirus.com, is a comprehensive academic search engine, including over 440 million scientific items, is used to search the above indicators in this study. Apart from the published scientific papers, other web sources, including the patents, scientists' homepages, courseware, current research progress *etc* can also be found in the 'Scirus' database (SCIRUS, 2011). According to the retrieval rating of each indicator in terms of the number of 'hit', the relative importance is ranked from 1 to 12, shown in Fig.8.1. Thus, the weight value can be calculated by Equation (8-1), based upon the importance ranking list. Table 8.2

shows the ‘binary-Dominance Matrix’ by using the Scirus example to determine the weight value.

8.2.3 Grey relation analysis

The grey decision approach derives from grey systems theory, which was proposed by Professor Julong Deng in 1982 and now has been developed to study those uncertain systems with poor or partially known information (Deng, 2000). The general decision models with grey elements or integrated with grey system models can be solved by means of grey analysis (Liu and Lin, 2006). In this study, grey relational analysis is the preferred method for selecting the environmentally friendly materials for further industrial application. The evaluation result can be interpreted as the ‘degree of grey incidence’, which is used to express the rates of change of the mathematical progressions relative to a baseline or an ideal progression (Liu and Lin, 2006). The greater the number of attributes that satisfy this condition, the greater the degree of grey incidence is (Zhai, Khoo & Zhong, 2008).

The basic model for grey decision-making can be described as the product of the weighting value and the result of grey relational analysis (Du, Pang & Wu, 2008), as follows:

$$R = W \times E \tag{8-2}$$

where $R = [r_1, r_2, \cdots, r_m]^T$ is the result vector of m evaluation objects, and $W = \sum_{k=1}^{n} W(k)$ is the weight value for each evaluation indicator. E is the matrix composed of all the evaluation indicators, in which $\delta_i(k)$ is the grey relational coefficient between the k^th^ indicator and the optimal indicator:

$$E = \begin{bmatrix} \delta_1(1) & \delta_1(2) & \cdots & \delta_1(n) \\ \delta_2(1) & \delta_2(2) & \cdots & \delta_2(n) \\ \vdots & \vdots & & \vdots \\ \delta_m(1) & \delta_m(2) & \cdots & \delta_m(n) \end{bmatrix} \tag{8-3}$$

Assume that the ideal index of evaluation indicators is $\beta^* = [\beta_1^*, \beta_2^*, \cdots, \beta_n^*]$, in which β_k^* is the optimal value for the k^{th} evaluation indicator. The ideal values are set depending upon how the indicators are viewed by manufacturer, *e.g.* some criteria need to be maxmised, *i.e.* materials recyclability, reusability, sales profit *etc*, and some should be minimised, *i.e.* energy consumption, health risk, manufacture cost *etc*. However, it is important to realize that the ideal value for each criterion shown in Table 8.1 should be set at an appropriate level, according to the technical and economic feasibilities within a specific manufacturer. Once β^* has been determined, a new grey relational matrix β can be constructed, where β_k^i is the original numerical value of the k^{th} indicator:

$$\beta = \begin{bmatrix} \beta_1^* & \beta_2^* & \cdots & \beta_n^* \\ \beta_1^1 & \beta_2^1 & \cdots & \beta_n^1 \\ \vdots & \vdots & & \vdots \\ \beta_1^m & \beta_2^m & \cdots & \beta_n^m \end{bmatrix} \tag{8-4}$$

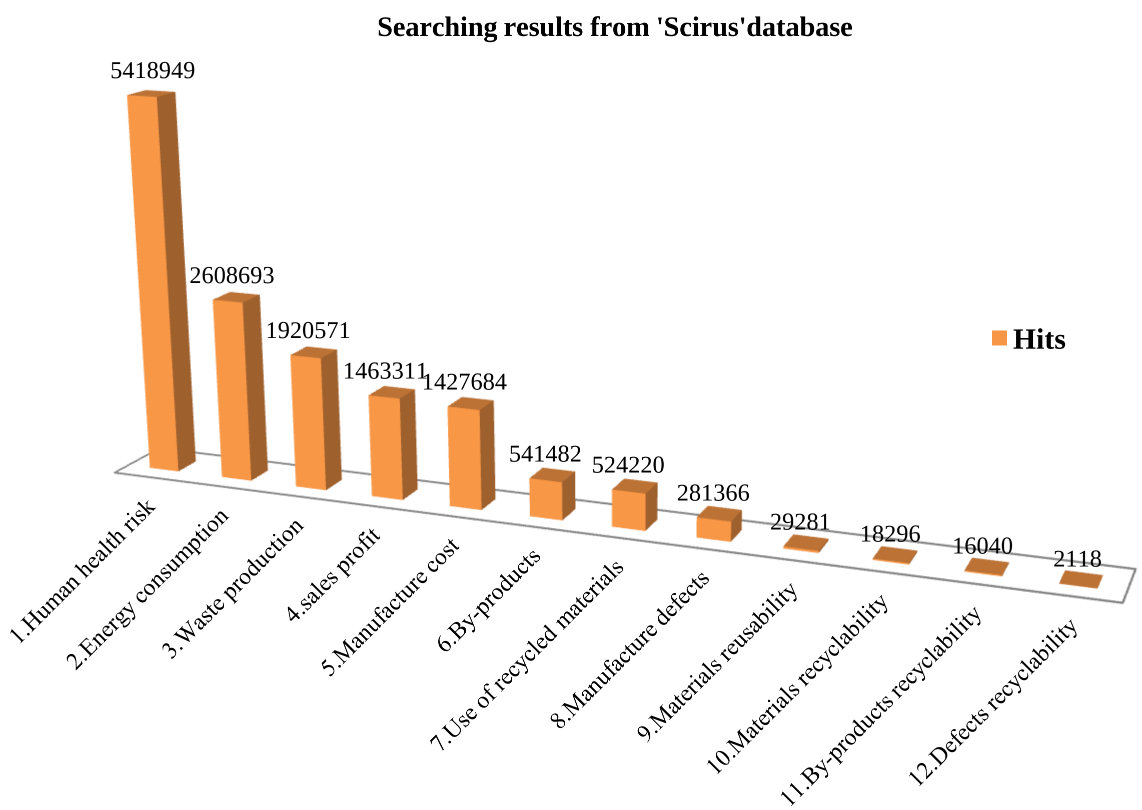


Fig.8.1. Relative importance of selected indicators as determined from a database search (updated by 14.10.2011)

Table 8.2 Binary dominance matrix complied using data from the Scirus database (Scenario one)

Indicators	1	2	3	4	5	6	7	8	9	10	11	12	Score	Weighting
1.Energy consumption	×	0	1	1	1	1	1	1	1	1	1	1	11	0.141
2.Human health risk	1	×	1	1	1	1	1	1	1	1	1	1	12	0.154
3.Materials recyclability	0	0	×	0	0	0	1	0	1	0	0	0	3	0.038
4.Materials Reusability	0	0	1	×	0	0	1	0	1	0	0	0	4	0.051
5.Use of recycled materials	0	0	1	1	×	1	1	0	1	0	0	0	6	0.077
6.Manufacture defects	0	0	1	1	0	×	1	0	1	0	0	0	5	0.064
7.Defects recyclability	0	0	0	0	0	0	×	0	0	0	0	0	1	0.013
8.By-products	0	0	1	1	1	1	1	×	1	0	0	0	7	0.090
9.By-products recyclability	0	0	0	0	0	0	1	0	×	0	0	0	2	0.026
10.Waste production	0	0	1	1	1	1	1	1	1	×	1	1	10	0.128
11.Manufacture cost	0	0	1	1	1	1	1	1	1	0	×	0	8	0.103
12.Sales profit	0	0	1	1	1	1	1	1	1	0	1	×	9	0.115

As the data collected for the selected evaluation criteria usually have different units, for instance energy consumption may be measured in kWh (Kilowatt hour), BTU (British Thermal Unit), J(Joule) *etc*, it is necessary to normalize these data, thus rendering them dimensionless for further evaluation. Further assume that the numerical value range of the k[th] criterion is $[\beta_{k1}, \beta_{k2}]$, in which β_{k1} is minimum among all the evaluation objects and β_{k2} is maximum, a dimensionless matrix α can be derived from β by means of the relation $\alpha_k^i = \dfrac{\beta_k^i - \beta_{k1}}{\beta_{k2} - \beta_{k1}}$ ($\alpha_k^i \in (0,1)$), as shown in expression (8-5). In this research, all the evaluation indicators have been normalized in terms of percentage.

$$\alpha = \begin{bmatrix} \alpha_1^{\,*} & \alpha_2^{\,*} & \cdots & \alpha_n^{\,*} \\ \alpha_1^{\,1} & \alpha_2^{\,1} & \cdots & \alpha_n^{\,1} \\ \vdots & \vdots & & \vdots \\ \alpha_1^{\,m} & \alpha_2^{\,m} & \cdots & \alpha_n^{\,m} \end{bmatrix} \tag{8-5}$$

In the matrix α, $\{\alpha^*\} = [\alpha_1^*, \alpha_2^*, \cdots \alpha_n^*]$ is set as the non-dimensional expected optimal sequence compared with the sequence of $\{\alpha\} = [\alpha_1^i, \alpha_2^i, \cdots \alpha_n^i]$. Thus, the grey relational coefficient can be calculated as follows:

$$\delta_i(k) = \frac{\min\limits_i \min\limits_k \left|\alpha_k^* - \alpha_k^i\right| + \varepsilon \max\limits_i \max\limits_k \left|\alpha_k^* - \alpha_k^i\right|}{\left|\alpha_k^* - \alpha_k^i\right| + \varepsilon \max\limits_i \max\limits_k \left|\alpha_k^* - \alpha_k^i\right|} \tag{8-6}$$

where ε is known as the distinguishing coefficient and $\varepsilon \in (0,1)$. Conventionally, and empirically, ε is set as 0.5 (Liu and lin, 2006), and this value is adopted in this study.

From the Equations (8-2) and (8-6), the grey decision-making model can be transformed as follows:

$$R_i = \sum_{k=1}^{n} W(k) \times \delta_i(k) \quad (8\text{-}7)$$

As R_i increases, $\{\alpha^i\}$ approaches more closely to the expecting optimal evaluation index $\{\alpha^*\}$. When R_i reaches the maximum value within the set of R, this is an indication that the i^{th} evaluation object is better than others. The evaluation result can be interpreted as the 'degree of grey incidence', which is used to express the rates of change of the mathematical progressions relative to a baseline or an ideal progression (Liu and Yi, 2006). In this study, the degree of grey incidence 'R_i' reflects how the data column of each evaluation object approximates to the set of ideal value index. The greater 'R_i' is, the closer the evaluated object approaches the ideal value set. Thus, different evaluated objects can be ranked in a sequence from the highest to the lowest grade. In addition, the evaluation object corresponding to the maximum grey correlative degree is deemed as the optimal object, and vice versa.

8.3 Case example

A leading handbag manufacturer in Guangdong Province, China, has kindly consented to their data being used for this case study. The material commonly used for handbags is PVC, and five grades with different compositions are investigated. The designations A, B, C, D and E are used to distinguish the five materials, shown in Fig.8.2. The purpose is to evaluate these five materials by means of the grey decision-making approach, and so determine which material is the most 'environmentally friendly'.

There are two evaluation scenarios: One is based upon the weight value determined by the keyword search from the ‘Scirus’ academic database, as shown in Fig.8.1. The other will apply the weighting value assigned by the product manager of the cited handbag manufacturer. Thus, the generated evaluation results will not only be compared with each other, but also analyzed in comparison with the current selection of materials used by the company.

Table 8.3 shows how to measure the selected criteria by using the five different grades of PVC materials. According to the measurements, the data collected from the handbag manufacturer have been processed dimensionlessly by percentage, as shown in Table 8.4. Moreover, some of the ideal values are set by the production strategies by the cited manufacturer. For example, the manufacturer expects to reduce the electricity consumed by the PVC material processing to 70%, as well as to reduce the manufacturing defects to 2% (See Fig.8.3a and Fig.8.3f). Similarly, the manufacturing cost should be minimized to 30%, whilst raising sales profit to 45% (See Fig.8.3k and Fig.8.3l). In addition, as previously mentioned some values, *e.g.* the human health risk, by-products, waste production, should be controlled as low as reasonable, ideally down to 0.0001%, 0.011% and 2%, respectively (See Fig.8.3b, Fig.8.3h and Fig.8.3j). On the other hand, others such as materials recyclability and reusability, need to be as high as possible, *e.g.* 98% and 0.23% (See Fig.8.3c and Fig.8.3d). Similarly, 93%, 95% and 0.20% are the representative ideal value selected from the criteria such as use of recycled materials, defects and by-products recyclability (See Fig.8.3e, Fig.8.3g and Fig.8.3i).

Table 8.3 Definition of measurements for environmental criteria

Indicators	Measurements
Energy consumption %	$E_c = \frac{E_c(i)}{E_t}$ where $E_c(i)$ is the energy consumed by using the ith material for industrial manufacture, E_t is the total energy consumed by the production, i=A, B, C, D, E. The energy used for PVC materials manufacturing is specified as electricity. For every 100 kWh electricity, 1 tonne material A will use 97 kWh for industrial processing, B 93.6 kWh, C 89.5 kWh, D 83.0 kWh and E 80.0 kWh.
Human health risk %	$R_h = \frac{R_h(i)}{R_t}$ where $R_h(i)$ is the health risk resulted from using the ith PVC material for industrial manufacture, R_t is the total health risk caused by using all kinds of the PVC materials for handbags production, i=A, B, C, D, E. $R_h(i) = P_e(i) \times C_e(i)$ where $P_e(i)$ is the probability of sudden environmental accidents during selection of the ith material for production, $C_e(i)$ is the consequence of the failure scenario in terms of the number of fatalities.
Materials recyclability %	$R_{ec} = \frac{Q_{rec}(i)}{Q_t(i)}$ where $Q_{rec}(i)$ is the quantity of recycled materials while using the ith PVC material for industrial processing, $Q_t(i)$ is the total quantity of the ith PVC material consuming, i=A, B, C, D, E.
Materials Reusability %	$R_{us} = \frac{Q_{us}(i)}{Q_t(i)}$ where $Q_{us}(i)$ is the quantity of reused materials while using the ith PVC material for industrial processing, $Q_t(i)$ is the total quantity of the ith PVC material consuming, i=A, B, C, D, E.
Use of recycled materials %	$R_{ur} = \frac{Q_{ur}(i)}{Q_{rec}(i)}$ where $Q_{ur}(i)$ is the usable quantity of the recycled materials, $Q_{rec}(i)$ is the quantity of recycled material while using the ith PVC material for industrial processing, i=A, B, C, D, E.
Manufacture defects %	$M_d = \frac{Q_d(i)}{Q_M(i)}$ where $Q_d(i)$ is the quantity of the manufacture defects, $Q_M(i)$ is the quantity of products (handbags) while using the ith material for industrial manufacturing, i=A, B, C, D, E.

Table 8.3 (Continued) Definition of measurements for environmental criteria

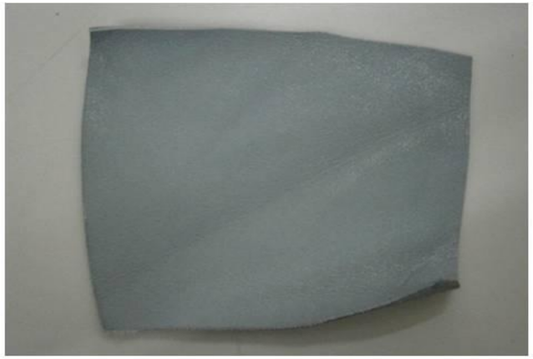
Indicators	Measurements
Defects recyclability %	$D_{rec} = \frac{Q_{rd}(i)}{Q_d(i)}$ where $Q_{rd}(i)$ is the quantity of the recycled manufacture defects, $Q_d(i)$ is the quantity of the manufacture defects while using the i^{th} material for industrial manufacturing, i=A, B, C, D, E.
By-products %	$B_p = \frac{Q_{bp}(i)}{Q_M(i)}$ where $Q_{bp}(i)$ is the quantity of the manufactured by-products, $Q_M(i)$ is the quantity of products (handbags) while using the i^{th} material for industrial manufacturing, i=A, B, C, D, E.
By-products recyclability %	$B_{rec} = \frac{Q_{brec}(i)}{Q_{bp}(i)}$ where $Q_{brec}(i)$ is the quantity of the recycled by-products, $Q_{bp}(i)$ is the quantity of the by-products while using the i^{th} material for industrial manufacturing, i=A, B, C, D, E.
Waste production %	$W_p = \frac{Q_{wp}(i)}{Q_t(i)}$ where $Q_{wp}(i)$ is the quantity of waste while using the i^{th} material for industrial processing, $Q_t(i)$ is the total quantity of the i^{th} material consuming, i=A, B, C, D, E.
Manufacture cost %	$C_M = \frac{C_M(i)}{C_t}$ where $C_M(i)$ is the cost by using the i^{th} material for industrial production, C_t is the total cost paid by using all kinds of the PVC materials for handbags production, i=A, B, C, D, E.
Sales profit %	$S_p = \frac{S_p(i)}{S_t}$ where $S_p(i)$ is the expected sales profit by using the i^{th} material for industrial production, S_t is the total expected sales profit gained by using all kinds of PVC materials for handbags production, i=A, B, C, D, E.

Table 8.4 Data for different indicators provided by a handbag manufacturer

Indicators%	Material A	Material B	Material C	Material D	Material E	Ideal value
Energy consumption	97.00	93.60	89.50	83.00	80.00	70.00
Human health risk	0.0015	0.0013	0.0005	0.0007	0.0002	0.0001
Materials recyclability	94.70	95.30	94.00	96.30	98.00	98.00
Materials Reusability	0.13	0.16	0.22	0.11	0.23	0.23
Use of recycled materials	90.80	91.00	91.90	92.70	92.00	93.00
Manufacture defects	8.10	7.30	5.80	6.00	5.00	2.00
Defects recyclability	90.00	93.00	93.60	89.00	94.00	95.00
By-products	0.020	0.017	0.013	0.013	0.011	0.011
By-products recyclability	0.12	0.14	0.16	0.10	0.20	0.20
Waste production	4.90	4.50	3.60	2.90	2.50	2.00
Manufacturing cost	42.00	38.00	32.00	34.00	28.00	30.00
Sales profit	40.00	39.80	38.60	35.70	31.00	45.00

Material A: 60% PVC, 21% Polyester, 19% Polyurethane

Material B: 60% PVC, 23% Polyester, 17% Polyurethane



Material C: 75% PVC, 11% Polyester, 14% Polyurethane

Material D: 85% PVC, 15% Polyurethane

Material E: 100% PVC

Fig.8.2. Five PVC materials with different compositions

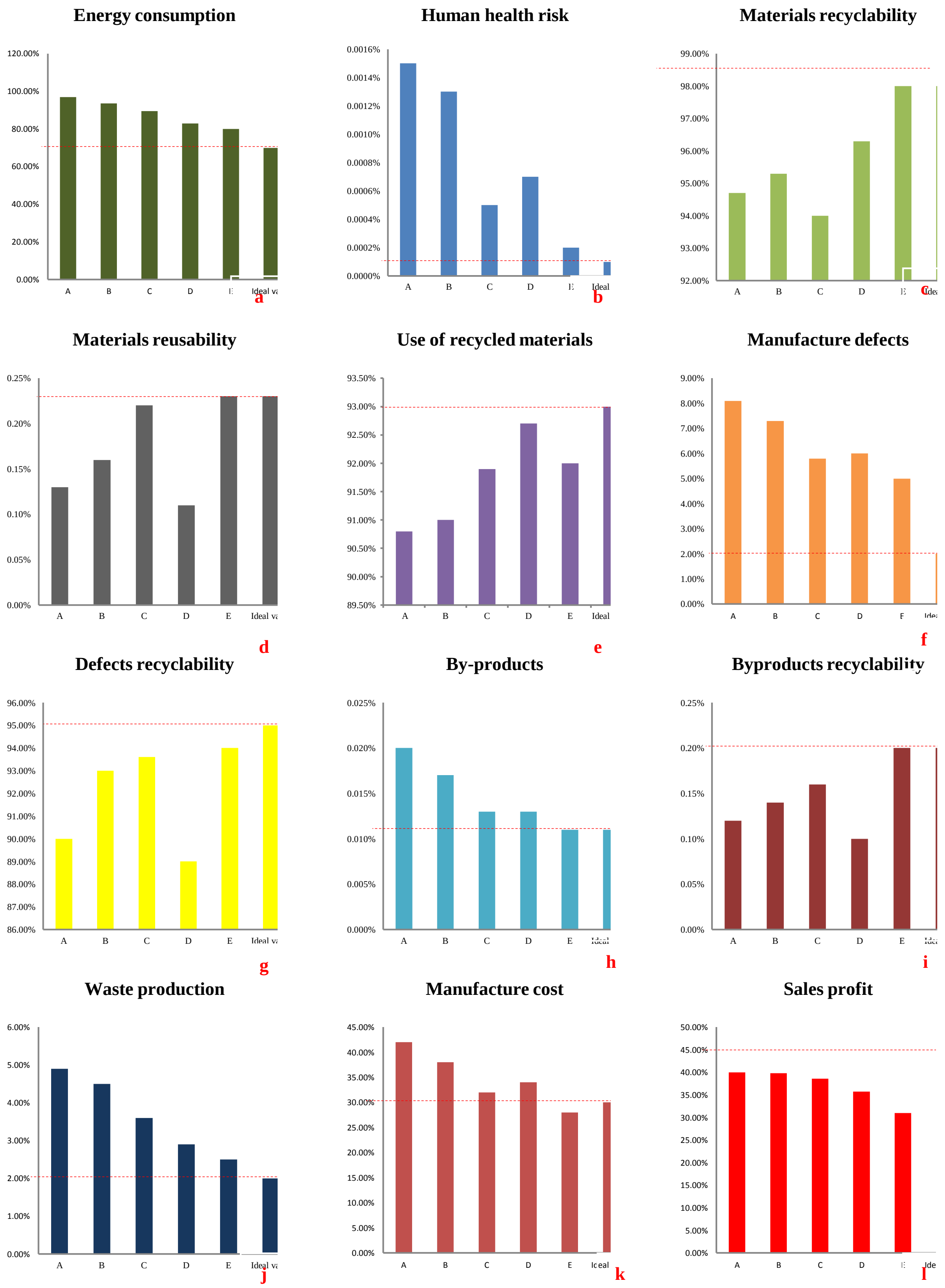


Fig.8.3. Comparison of five PVC materials within different criteria in the case example

8.3.1 Evaluation scenario one

Scenario one will use the set of weight values determined by the 'Scirus' search example for the evaluation. In order to help the engineer or designer employ the grey analysis more conveniently, as well as simplify the computation complexity, this approach has been embodied into a decision support tool based on a spreadsheet calculation (Microsoft Excel 2007). The decision support tool has been divided into two modules, representing the input parameters and the output of the analysis results. Fig.8.4 depicts a screen shot of the input module, starting with the weighting value determination by marking 1 or 0 in the designed 'binary-dominance matrix' table (See Fig.8.4a first step), followed by entering the numerical value for each indicator derived from the case example (See Fig.8.4b second step). When all the information has been submitted, the evaluation result of scenario one can be calculated by means of the spreadsheet, as shown in Table 8.5.

Table 8.5 Grey evaluation result of scenario one

Grey incidence (R_i)	Material A	Material B	Material C	Material D	Material E
R_A	0.7615				
R_B		0.7835			
R_C			0.8227		
R_D				0.8270	
R_E					0.8456

As can be seen from the Table 8.5, $R_E>R_D>R_C>R_B>R_A$, material E is the optimum material from an 'environmentally friendly' point of view, material A being the worst choice in this scenario.

Materials Selection:An Environmental Evaluation Approach

First step: weight determination		Energy consumption %	Human health risk/toxity	Materials Recyclability %	Materials Reusability %	Use of recycled materials %	Manufacture defects %	Defects recyclability %	By-products %	By-products recyclability %	Waste production %	Manufacture cost %	Sales profit %	Total Score	Weight Value
1	Energy consumption %		0	1	1	1	1	1	1	1	1	1	1	11	0. 141025641
2	Human health risk/toxity	1		1	1	1	1	1	1	1	1	1	1	12	0. 153846154
3	Materials Recyclability %	0	0		0	0	0	1	0	1	0	0	0	3	0. 038461538
4	Materials Reusability %	0	0	1		0	0	1	0	1	0	0	0	4	0. 051282051
5	Use of recycled materials %	0	0	1	1		1	1	0	1	0	0	0	6	0. 076923077
6	Manufacture defects %	0	0	1	1	0		1	0	1	0	0	0	5	0. 064102564
7	Defects recyclability %	0	0	0	0	0	0		0	0	0	0	0	1	0. 012820513
8	By-products %	0	0	1	1	1	1	1		1	0	0	0	7	0. 08974359
9	By-products recyclability %	0	0	0	0	0	0	1	0		0	0	0	2	0. 025641026
10	Waste production %	0	0	1	1	1	1	1	1	1		1	1	10	0. 128205128
11	Manufacture cost %	0	0	1	1	1	1	1	1	1	0		0	8	0. 102564103
12	Sales profit %	0	0	1	1	1	1	1	1	1	0	1		9	0. 115384615

a

Second step: Parameters Determination		Input name: Material A	Input name: Material B	Input name: Material C	Input name: Material D	Input name: Material E	Ideal Parameters
1	Energy consumption %	97	93.6	89.5	83	80	70
2	Human health risk/toxity	0.0015	0.0013	0.0005	0.0007	0.0002	0.0001
3	Materials Recyclability %	94.7	95.3	94	96.3	98	98
4	Materials Reuseability %	0.13	0.16	0.22	0.11	0.23	0.23
5	Use of recycled materials %	90.8	91	91.9	92.7	92	93
6	Manufacture defects %	8.1	7.3	5.8	6.0	5	2
7	Defects recyclability %	90	93	93.6	89	94	95
8	By-products %	0.02	0.017	0.013	0.013	0.011	0.011
9	By-products recyclability %	0.12	0.14	0.16	0.1	0.2	0.2
10	Waste production %	4.9	4.5	3.6	2.9	2.5	2
11	Mannufacture cost %	42	38	32	34	28	30
12	Sales profit %	40	39.8	38.6	35.7	31	45

b

Fig.8.4. Screen shot of the decision support tool in the evaluation scenario one

8.3.2 Evaluation scenario two

In this scenario, the product manager in the cited handbag manufacturer was requested to rank the importance of each criterion, which can lead to a more realistic evaluation. In the ‘Scirus’ example shown in the scenario one, each indicator was scored using value 1 or 0. In scenario two, the product manager has classified the evaluation criteria as seven levels in terms of their relative importance (See Fig.8.5), and since some indicators are incorporated into the same level, these are scored 0.5 for each. Table 8.6 shows the ‘binary dominance matrix’ in terms of the importance hierarchies, defined in Fig.8.5. The evaluation results are shown in Table 8.7. This confirms that, whilst the sequence has changed ($R_E > R_C > R_D > R_B > R_A$), material E is still the most ‘environmentally friendly’ material among the five PVC materials, with material A the least.

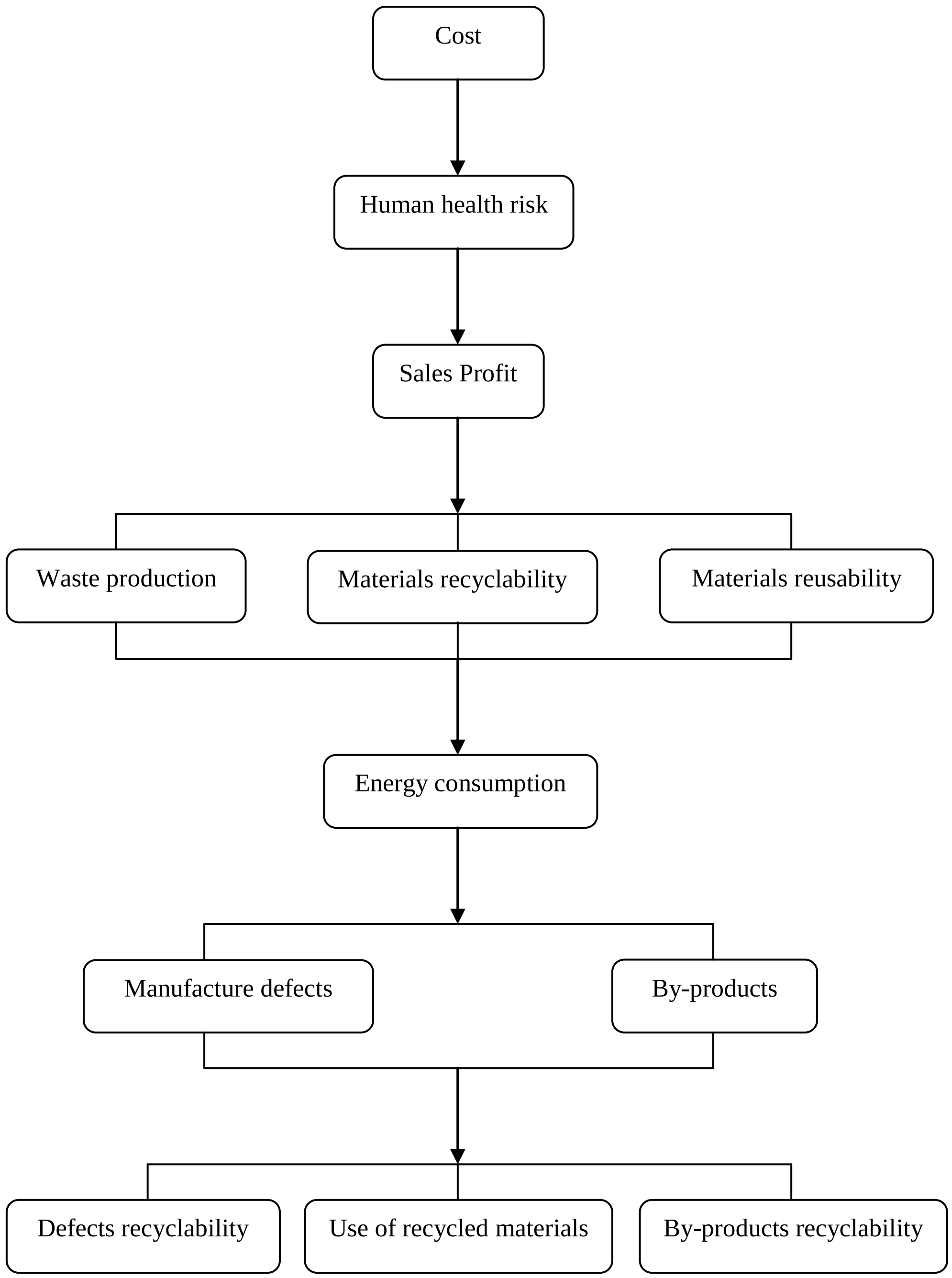


Fig.8.5. Levels of evaluation criteria ranked by the cited handbag manufacturer

Table 8.6 Binary dominance matrix of the case example (scenario two)

Indicators	1	2	3	4	5	6	7	8	9	10	11	12	Score	Weighting
1.Energy consumption	×	1	0	1	1	1	1	1	1	0	0	0	7	0.089
2.Human health risk	1	×	1	1	1	1	1	1	1	1	0	1	11	0.139
3.Materials recyclability	1	0	×	0	1	1	1	1	1	0.5	0	0	8	0.101
4.Materials Reusability	1	0	0.5	×	1	1	1	1	1	0.5	0	0	8	0.101
5.Use of recycled materials	0	0	0	1	×	0	0.5	0	0.5	0	0	0	2	0.025
6.Manufacture defects	0	0	0	1	1	×	1	0.5	1	0	0	0	4.5	0.057
7.Defects recyclability	0	0	0	0	0.5	0	×	0	0.5	0	0	0	2	0.025
8.By-products	0	0	0	0	1	0.5	1	×	1	0	0	0	4.5	0.057
9.By-products recyclability	0	0	0	0	0.5	0	0.5	0	×	0	0	0	2	0.025
10.Waste production	1	0	0.5	0.5	1	1	1	1	1	×	0	0	8	0.101
11.Manufacture cost	1	1	1	1	1	1	1	1	1	1	×	1	12	0.152
12.Sales profit	1	0	1	1	1	1	1	1	1	1	0	×	10	0.127

Table 8.7 Grey evaluation result of scenario two

Grey incidence (R_i)	Material A	Material B	Material C	Material D	Material E
R_A	0.7684				
R_B		0.7960			
R_C			0.8365		
R_D				0.8301	
R_E					0.8608

8.3.3 Results and discussions

According to the evaluation results of scenarios one and two, the variation of weighting value plays an important role in the sensitivity of the grey relational model, other model parameters being fixed. Thus, the importance of energy consumption has remarkably decreased from 0.141 in Table 8.2 to 0.089 in Table 8.6, use of recycled materials from 0.077 to 0.025, by-products from 0.090 to 0.057 and waste production from 0.128 to 0.101. On the other hand, manufacturing cost and sales profit are raised significantly from 0.103 to 0.152, from 0.115 to 0.127, respectively, as well as the materials recyclability and reusability, from 0.038 and 0.051 to 0.101. The remaining indicators are little changed, *e.g.* human health risk and manufacture defects reducing from 0.154 to 0.139, from 0.064 to 0.057, separately, defects recyclability increasing from 0.013 to 0.025. Thus, the evaluation result has slightly altered, from which material C is superior to material D in the scenario two. Both scenario one and two suggest that material E is most ‘environmental sound’, while material A ‘environmentally unfriendly’.

The actual consumption of these five PVC materials used by the cited manufacturer has been investigated. Material C has the highest consumption rate for handbag production, followed by materials E, D, B, and A, *i.e.* $M_C>M_E>M_D>M_B>M_A$, which reflects that the material selection for handbag production is, in reality, strongly influenced by criteria such as ‘market demand’, ‘materials performance’, and ‘cost-benefit’ (Edwards, 1994; Ljungberg and Edwards, 2003; Ashby, 2005). In other words, apart from product functionality and company profitability, popular fashion is also a fundamental driver in product design. In terms of ‘cost-benefit’, Table 8.4 shows that material A has the highest manufacturing cost, whilst it also contributes the highest proportion of profits, both about 40%. Comparatively speaking, the processing cost of material C (about 32%) is less than material A (about 42%), but it yields higher profit (38.6%). ‘Materials performance’ is mainly related to the properties of materials, which affects the quality of products. For the PVC materials used in the present case, the laboratory performance tests include a mechanical fatigue test, chemical corrosion test by means of salt spray, oven test for thermal expansion and a colour fastness test (Allen, 2011; SATRA Technology, 2011; Winckle, 2011). According to the test results, material C shows the best abrasive resistance, decay, heat resistance, and colour fastness. However, material A shows poor performances, for example, the surface is easily rubbed off during the process of manufacture.

In addition, it can be identified that the sequence of actual materials consumption ($M_C>M_E>M_D>M_B>M_A$) is quite similar to the result from grey relational analysis ($R_E>R_C>R_D>R_B>R_A$) in the case example. Material C shows not only the highest consumption rate for handbag production, but also the second highest degree of grey incidence. Although material E is superior to C in terms of grey evaluation result, the actual consumption of material E is less than C. This is because material C is more favorable as the main material, while material E is more commonly used as an auxiliary material for handbag design. Thus, material C can be determined as the near optimal choice. It is suggested, therefore, that the actual consumption of material could be integrated into the environmental evaluation to aid decision making on materials selection. In this case study, both materials E and C emerge as ‘environmentally friendly’ for cleaner production, while the use of material A should be reduced or eliminated all together from the manufacturing process.

Previous studies have concentrated on the selection of materials with widely differing characteristics. The present study confirms that our evaluation methodology is capable of discriminating between materials with similar manufacturing and environmental characteristics. In addition, our calculation tool can be used for a wide range of materials selection scenarios.

8.4 Summary

This Chapter uses a grey relational analysis approach for application to aid decision-making on materials selection for cleaner production for application by engineers. The starting point of this study is to determine the environmental evaluation criteria and to assign a weighting value in terms of their importance. A case example is provided, in which five PVC materials have been subjected to environmental evaluation to determine their sustainability for handbag manufacture. In order to assist engineers in the application of the grey evaluation process for materials selection, and to simplify the computational complexity, a calculation support tool based on a spreadsheet calculation has been developed. The associated grey relational result analysis of the case example is discussed. Chapter 9 provides the discussions and conclusions for the PhD study, laying a foundation for further work.

Chapter 9: Conclusions and Further Study

9.1 Discussion

This PhD study focuses on the design of an environmental management system for hazardous waste materials to minimize environmental impact, *i.e.* environmental risk and carbon emissions, by which new understanding and novel solutions would be provided with regard to societal change in the context of "sustainable development". In particular, this research is directed towards to persuading consumers to adjust their purchasing behaviour to mitigate climate change, thus promoting sustainable production whilst maintaining industrial competitiveness, and to demonstrate sustainability for environmentally friendly products with due regard to the Triple Bottom Line (TBL).

The study seeks to raise consumers' awareness of climate change, and thus to help change their lifestyles and purchasing behaviours. In this context, a dimensionless system of carbon labelling has been proposed, which could increase the ability of green consumers to implement their concerns in the market place. However, it should be acknowledged that an indicator never becomes of better quality than the input of which it is based (See the detailed discussions in Chapter 3). For instance, the proposed indicator 'Carbon Emissions Intensity Ratio' (CEIR) is highly dependent upon the variance of Life Cycle Assessment (LCA) emissions data. Moreover, the dimensionless carbon labelling indicator is seen to be influenced by short term price fluctuations and the precision of the calculated baseline, *i.e.* national carbon emissions per GDP.

An important assumption is that purchasing preference can be influenced by education in green and low carbon issues to increase demand for more environmentally friendly products, thus in turn to promote sustainable production by manufacturers. However, a greater level of governmental intervention, in the form of manufacturing process regulation might be necessary to achieve this. Game theory provides a novel perspective that models the likely behaviour of manufacturers and government in response to minimizing environmental impact, whilst increasing performance along the three dimensions of the Triple Bottom Line (Economic, Society and Environment). However, the influence of such factors as living standards, public purchasing behaviour etc., have yet to be considered in this study. The interactions between the upstream and downstream businesses, as well as between the enterprises and customers have been omitted. Furthermore, the manufacturers are considered as one entity, regardless of the scale, quantity and quality of productions. Similarly, government is accorded as a generic role without distinction of identity, e.g. National government or European Union (EU) Committee.

In order to provide better, safer and sustainable products for public consumption and achieve long term commercial success, careful materials selection is becoming an increasingly important aspect of product design. This PhD study mainly focuses on a simple approach for engineering designers to use, by integrating binary-dominance matrix with grey relational analysis to aid decision-making on materials selection while taking environmental evaluation into account. The majority previous studies have used the life cycle assessment (LCA) approach to materials selection when considering environmental impact, *e.g.* Eco-indicator 99, which is still a complex process involving a large amount of input data (Yang, 2007; Zhou, Yin and Hu, 2009). Moreover, this work mainly especially contributes a selection approach between similar materials (including type and composition) to further improve the environmental performance of the product. Although the proposed approach shows promise, it is necessary to test the validity and sensitivity of the grey evaluation model further by applying it to a wider variety of case studies.

9.2 Conclusions

The main contribution of this PhD study can be reflected in the several aspects, *i.e.* the identification a new indicator to appreciate the understanding of carbon footprint and thus to improve the existing carbon footprint label; the application game theory to aid decision support by seeking the optimal or near-optimal strategies for environmental risk and carbon footprint reduction to achieve more environmentally friend products; the development a novel convenient approach for materials selection to promote cleaner production. All the detailed investigations in this study and the recommendations for future study are reviewed below.

A review of the literature is necessary to set this research in context, relating to the following topics: hazardous materials, hazardous waste, waste management, environmental risk, carbon footprint, game theory application, and decision support systems. The review supports the research aim and objectives, which is an essential point in the development of a novel environmental risk management system for hazardous waste materials.

Current carbon labelling scheme is considered not easily to be understood by consumers thus leading to further improvement. This study achieves the first research objective by identifying a novel dimensionless indicator Carbon Emissions Intensity Ratio (CEIR) to present the carbon labelling in a more intuitive way, as well as to help consumers raise the awareness of environmental impact, *i.e.* carbon footprint. The carbon emissions from LCA are normalized as Carbon Emissions Intensity (CEI), whilst the dimensionless indicator CEIR is established based upon the CEI's ratio to the overall national carbon emissions intensity. Carbon emissions intensity ratios of a comprehensive range of products are calculated and assigned to different ratio levels, to show how to employ this approach. It is apparent that heavy industrial products generate the highest carbon emissions intensity ratio, and groceries the lowest. Seven products are identified with extremely high emissions intensity ratio, accounting for 11.7% of the total sixty products.

Game Theory offers an effective approach to formulating a dominant strategy designed to increase performance across the three dimensions of the Triple Bottom Line (Economic, Society and Environment). This study has applied game theory to better understand the dilemmas that can exist between government and manufacturers, as well as provide insightful perspectives on the potential problems in the context of cleaner production. Three game scenarios have been developed sequentially which reflect the possible changes in the actions of government and manufacturers to achieve more environmentally friendly products. The established game model mainly depends upon the variation of the following three important factors, such as innovation cost (C), economic penalty (P) and additional sales of 'environmentally friendly products' (S). Through the analysis of several game scenarios, it is concluded that the behaviours of the main players, in this case, government and manufacturers, can be seen to be best achieved by cooperation driven by a combination of regulation pressure and consumer preference.

Game theory approach also informs government and manufacturers' decision making ability on the appropriate extent of risk and carbon footprint reduction in the green supply chain. Different strategies have been initially identified and compared in order to limit the potential environmental impact, by reducing the risk and the carbon emissions, whilst maximizing the economical benefits, by inclusion of the principle of the ‘tolerability of risk’. Moreover, major factors have been identified by the construction of the game model, such as cost and benefit, governmental punitive and incentive policy *etc*, to provide insight into the problem situation.

Environmental consideration is an increasingly important component in materials selection, in order to adapt product design to promote cleaner production, provide sustainable products for public consumption and achieve long term commercial success. This study has introduced a convenient approach by integrating ‘Binary Dominance Matrix’ with grey relational analysis for application by engineering designers to aid decision-making on materials selection while taking environmental evaluation into account. Five PVC materials, designated as A, B, C, D and E, have been investigated to identify which one is the most ‘environmentally friendly’ for future handbag manufacture. The evaluation result has been compared with the actual materials consumption in the representative handbag manufacturer in order to select which material is the most ‘environmentally friendly’. It is concluded that both materials E and C emerge as ‘environmentally friendly’ for cleaner production, while the use of material A should be reduced or eliminated all together from the manufacturing process. In addition, this integrated evaluation approach is flexible which can provide an environmental index to judge a range of materials.

It is concluded that this study provides a decision support tool for use by engineering designers to minimize the risk, and the carbon footprint, from hazardous materials in product design, through the application of ‘game theory’, ‘grey theory’ *etc*, as well as various computational approaches, by helping the designer identify novel solutions or mitigation strategies.

9.3 Further study

The research work offers an approach to maintain competitiveness as well as demonstrate sustainability for products, *i.e.* economic, social and environment dimensions. This can be true for all developed economies, as the need to reduce environmental impact increases in importance and consumers may become more sophisticated in their buying habits. However, there are still some limitations in the system study, *e.g.* carbon labelling scheme, game theoretical analysis and materials selection, which lay a foundation for further work, ultimately to provide appropriate solutions, mitigation strategies for designers, engineers and policy makers to minimize the environmental impact. The recommended future studies are presented in the following sections.

9.3.1 Carbon labelling improvement

The evaluation criteria for carbon footprint intensity in Chapter 3 are based on the assumption that all the products analyzed are subject to the assumed normal distribution, and this may result in uncertainties of criteria definition. Thus, a wider range of products and specific case scenarios need to be examined to confirm the validity and sensitivity of this approach. With regard to carbon labelling, whether the form of label suggested here, based upon the carbon footprint intensity, is easily understood by consumers needs to be established through questionnaires, focus groups and interviews.

9.3.2 Game theory for decision making

With regard to the 'cleaner production' game presented in the Chapter 5, there are still some limitations involved in the game model and simulation. First of all, the manufacturers are considered one entity, regardless of the scale, quantity and quality of productions, economic benefit and selected strategies, *etc*. Secondly, in order to simplify the analysis of game simulation, the factor of tax break has been fixed, and consequently the selection of strategic choice will be influenced. Moreover, the interactions between the different organisations, enterprises and customers have been omitted. Further study will focus on the underlying mathematical modelling for the game representing the complexity between government, manufacturers and other stakeholders, as well as the development of game simulation in different scenarios. Moreover, it is expected the game model can be fully quantified for further application by means of integration with case studies.

Similarly, when discussing game theory application to the supply chain (in Chapter 6), it is expected that the mathematical model can be fully quantified for further application by means of integration with more case studies. The priority of reducing environmental risk and carbon footprint in different scenarios of the supply chain network will also be considered.

The game theoretical approach in this study mainly focuses on the static normal form game to provide strategies selected by government and manufacturers. Future study could discuss other game forms, such as dynamic, repeating, signal game *etc* (Rasmusen, 2007). Moreover, the game relationship can be more interactive, not only restricting it to the non-cooperative game, but also developing it as an evolutionary or cooperative game.

9.3.3 Materials selection

In this study, the evaluation criteria for materials selection are generic in the context of 'sustainable development'. This situation can be improved further to involve other typical parameters considered during the process of materials selection, *e.g.* physical and chemical properties of materials, materials performance for the specific process industries, thus to make the evaluation results more convincing in various application scenarios. Secondly, the 'Binary Dominance Matrix' can be improved by using alternative methods of weight determination, *e.g.* Analytic Hierarchy Process (AHP), Entropy method, fuzzy logic *etc* to compare their accuracy. In addition, the computational tool can also be improved by including other important aspects such as market demand and materials performance. It is expected that this approach can be applied to more case scenarios, to examine the validity and sensitivity of the grey evaluation model.

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Appendix A: User manual for decision support tool

A.1 System introduction and requirement

This appendix demonstrates a ‘decision support tool’ for application by engineering designers and policy makers to reduce the environmental risk and the associated carbon footprint, as well as to help the designer identify novel solutions, mitigation strategies and select appropriate materials for cleaner production. This decision support tool is entitled “Environmental Risk Management System for Hazardous Waste Materials”, developed and encapsulated by the Visual Basic 6.0 programming (See Fig.A.1.1). The decision support tool should be operated based upon the “Windows XP” system or even a higher system, *i.e.* “Windows 7”. Moreover, the Windows operation system should install the ‘Microsoft Excel 2007’ or even higher ‘Microsoft Excel 2010’ for further application.

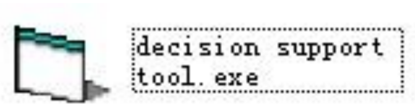


Fig.A.1.1. Installation of the developed decision support tool

While double clicking on the ‘decision support tool’.exe, there are five sub modules within the tool, ‘carbon footprint of products and carbon footprint intensity’, ‘Gambit simulation’, ‘environmental impact assessment (Carbon footprint measurement)’, ‘Two player’s game for decision-making’ and ‘materials selection for cleaner industrial application’. Each sub-module can be accessed by clicking the corresponding button in the interface of the decision support tool (See Fig.A.1.2). The detailed functionality of each sub-module is introduced in the following sections.

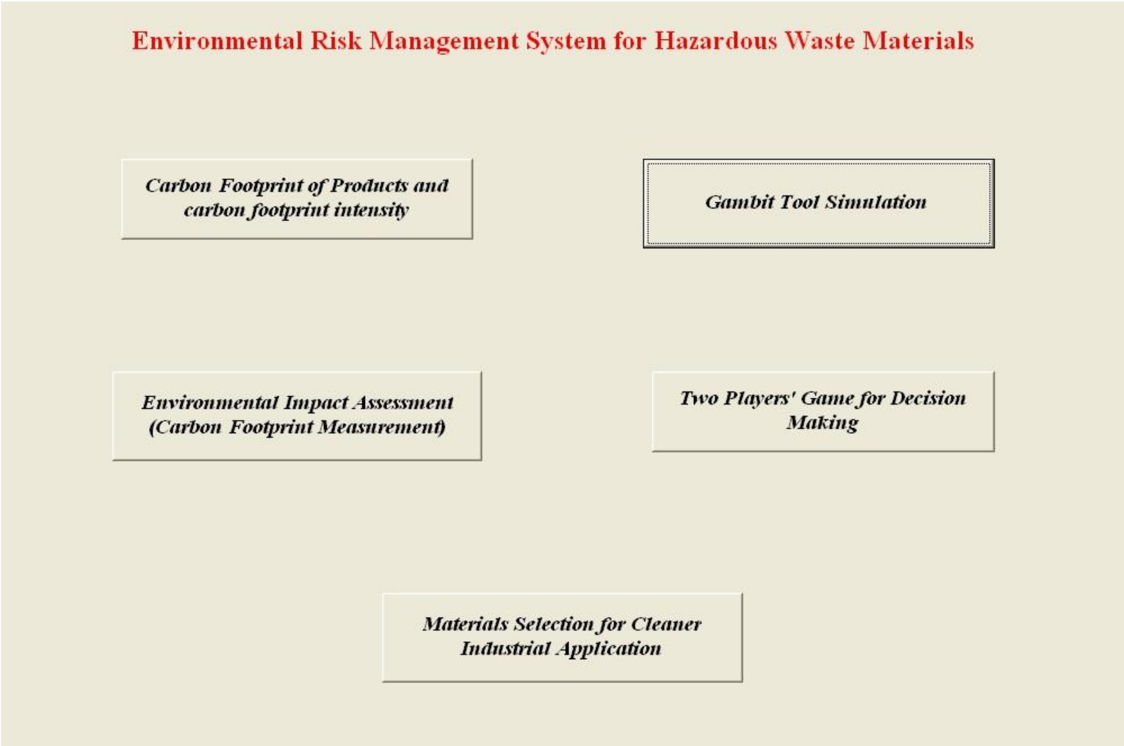


Fig.A.1.2. Interface of the developed decision support tool

A.2 Products' carbon footprint and intensity

This module is used to measure the various products' carbon footprints and their corresponding carbon footprint intensity (CFI), which has been defined in the Chapter 3. The products have been categorized into five groups in terms of their applications, *e.g.* heavy industrial products, light industrial products, food and drink and 'other commercial' products. The carbon footprint emission factors, derived from an input-output model developed by Small World Consulting Ltd, in collaboration with Lancaster University (Berners-Lee, 2010), have been converted to carbon footprint intensity in units of kilograms per Pound Sterling (£) of output based on the retail prices.

The first frame shows the carbon footprint measurement for heavy industrial products, in which coal, oil and gas, metal ores, coke *etc.*, is included (See Fig.A.2.1). The product type, annual expense, emissions factor and carbon footprint are shown in the left side, whilst the carbon footprint intensity of each product is set to display in the right side. In addition, there are five buttons in the left corner, as '**Calculation**', '**Show carbon footprint intensity**', '**Clear**', '**Next group of products**', '**Return**', respectively.

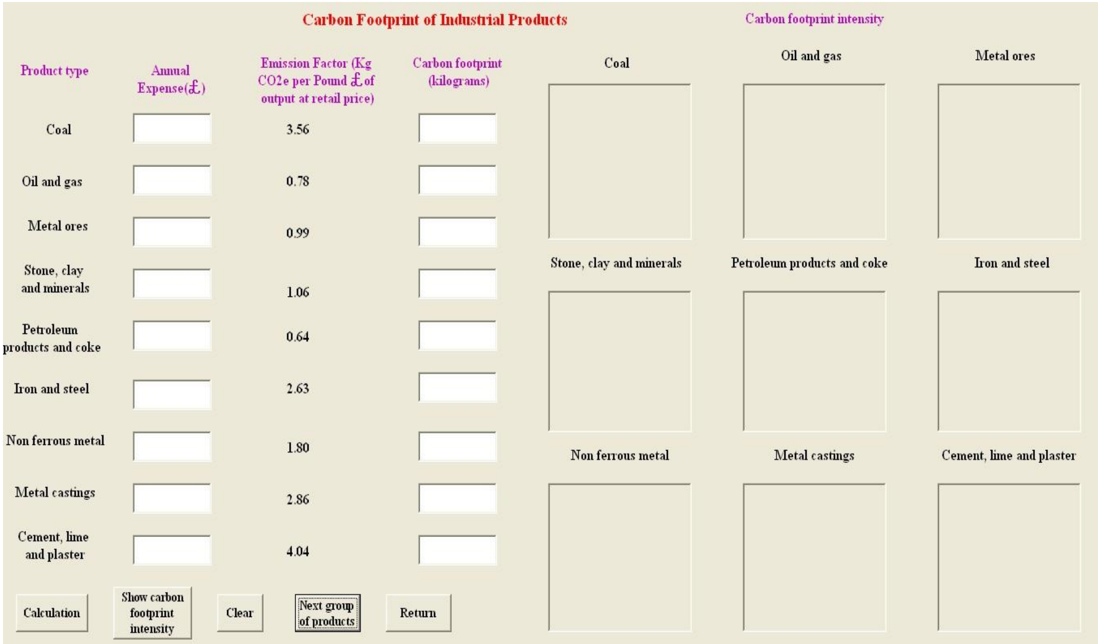


Fig.A.2.1. Carbon footprint measurement for heavy industrial products

Here, '1 pound' is assumed to be the annual expense for each product as a representative example to demonstrate how to operate the functional module. While filling out the annual expense for each heavy industrial product in terms of British Pounds (£), the corresponding carbon footprint will be calculated by clicking the button '**Calculation**' and shown in the output boxes. Once clicking the button '**Show carbon footprint intensity**', the risk-based diagram for each product will be displayed, *e.g.* coal, iron and steel, metal casting and cement show high carbon footprint intensity (See Fig.A.2.2). If the annual expense of certain product needs to be revised, or if the carbon footprint requires calculating again, click the '**Clear**' button to eliminate the previous input. Click the '**Return**' button to escape this functional module, whilst switching to the main frame of the decision support tool.

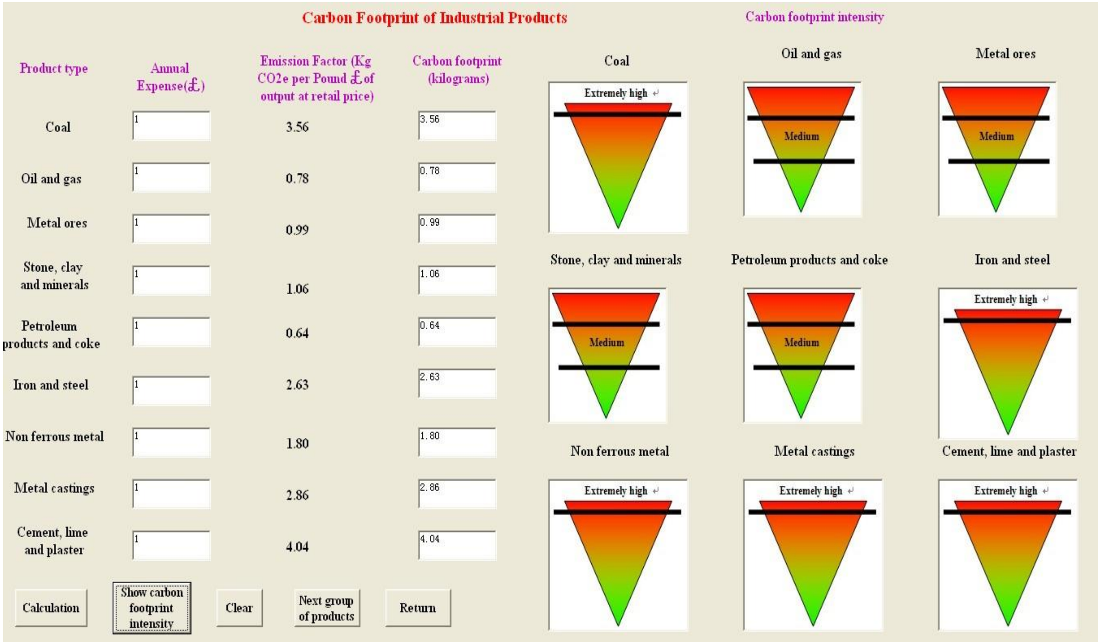


Fig.A.2.2. Carbon footprint and its intensity for heavy industrial product

Click the button '**Next group of products**', the modular frame will be switched to the carbon footprint measurement for light industrial products (See Fig.A.2.3). Similar to the above assumption, '1 pound' is representative to be the annual expense for each product. Fig.A.2.4 shows the corresponding carbon footprint in the output box, once inputting the annual expense for each heavy industrial product in terms of British Pounds (£). Furthermore, the carbon footprint intensities for all the products are displayed in the assigned frame, by clicking '**Show carbon footprint intensity**' at the left corner. Click the '**Return**' button to return to the interface of carbon footprint measurement for heavy industrial products.

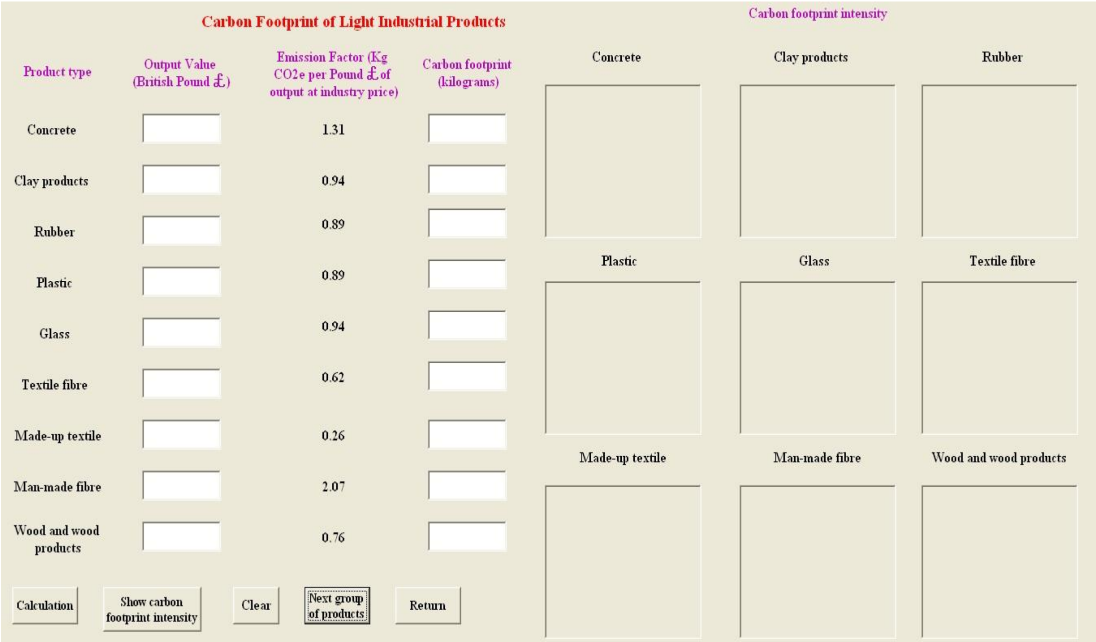


Fig.A.2.3. Carbon footprint measurement for light industrial products

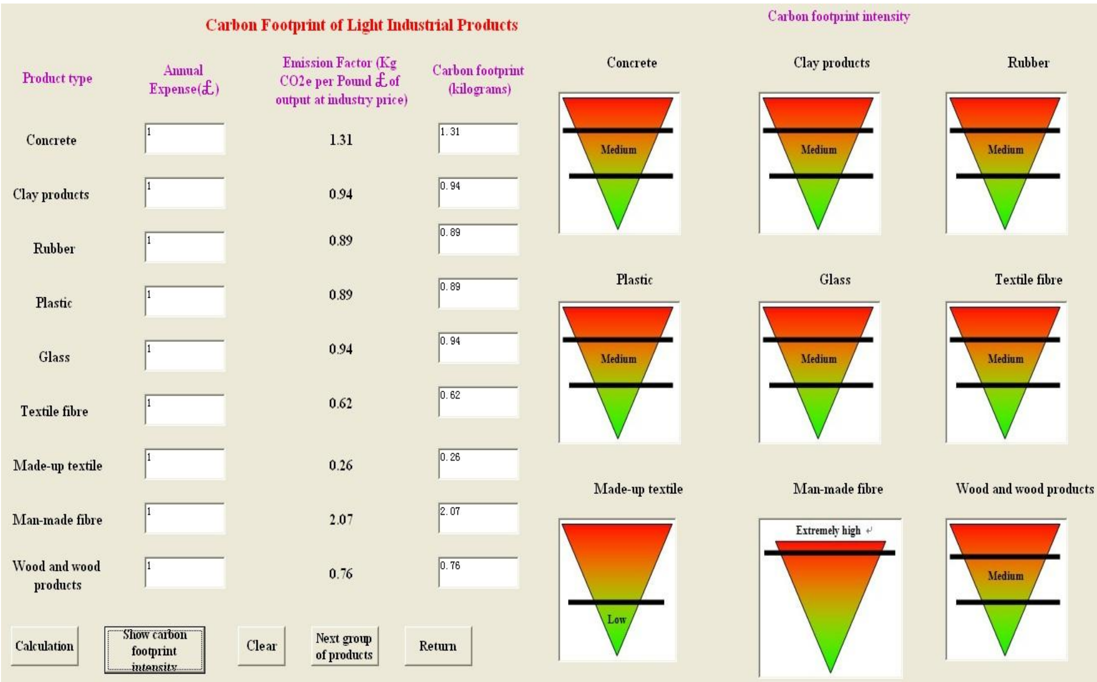


Fig.A.2.4. Carbon footprint and its intensity for light industrial product

The next group of products is 'food and drink', including the processed meat, oils, fruit, dairy products, soft drinks *etc* (See Fig.A.2.5). While submitting '1' as the representative annual expense to each input box, the corresponding carbon footprint can be calculated by clicking the button '**Calculation**'. Subsequently, the carbon footprint intensity for each product is show in the right side (See Fig.A.2.6).It is clear that the carbon footprint intensity of food and drink is lower than industrial products. If the annual expense of certain product needs to be revised, or if the carbon footprint requires calculating again, click the '**Clear**' button to eliminate the previous input.

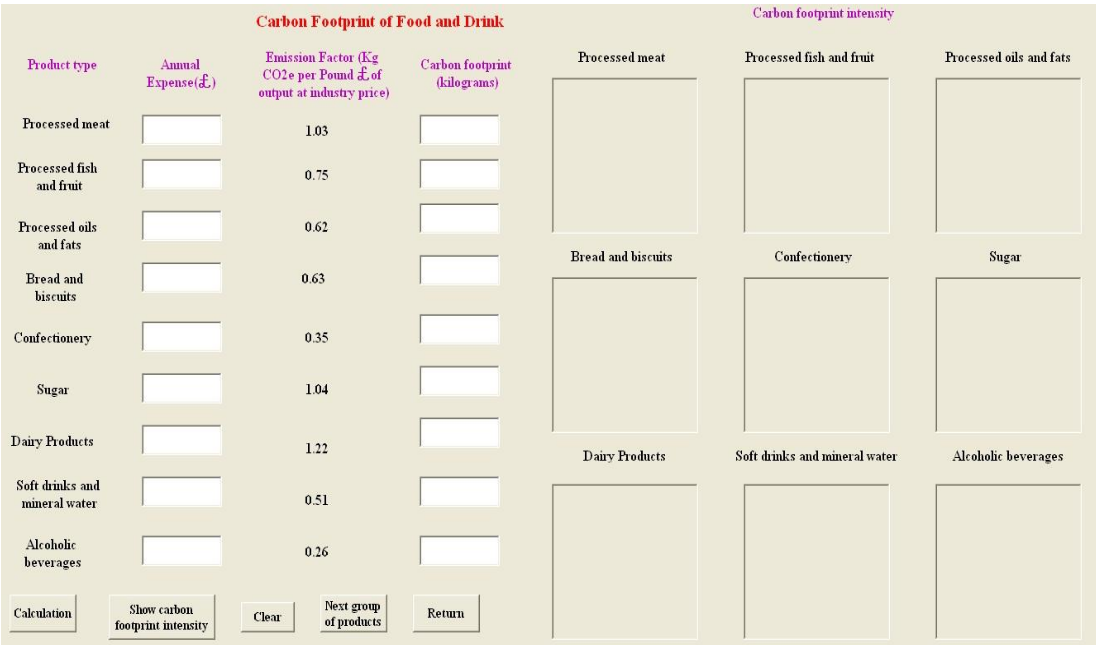


Fig.A.2.5. Carbon footprint measurement for food and drink

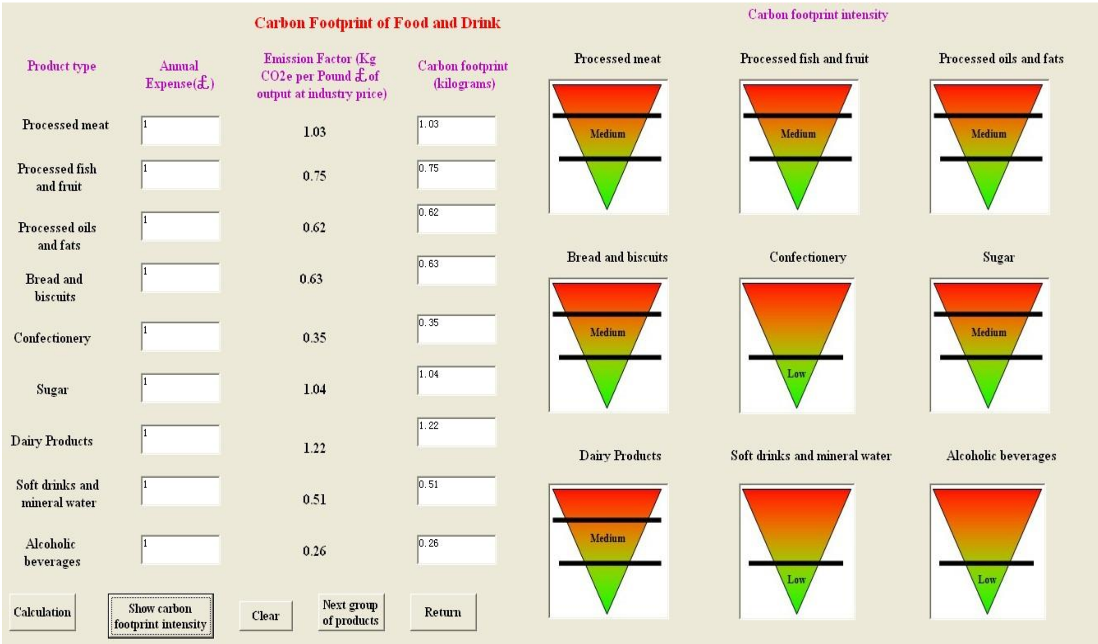


Fig.A.2.6. Carbon footprint and its intensity of food and drink

There are 18 products in the category of house-ware, such as furniture, domestic appliances, cutlery *etc*, which have been displayed in two forms of the system module. While still using '1' pound as the annual expense for each household product, the corresponding carbon footprint can be derived from clicking the button '**Calculation**'. Similarly, once clicking the button '**Show carbon footprint intensity**', the risk-based carbon labelling diagram for each product will be displayed (See Fig.A.2.7 and Fig.A.2.8). It is clear that heavy industrial products generate the highest carbon footprint, in which all the products are identified as having at least medium carbon footprint intensity, with five precursor materials being extremely high. However, light industrial products contribute lower carbon emissions than heavy ones, and the group of groceries shows the least carbon footprint intensity compared with heavy and light industrial products. If the annual expense of certain product needs to be revised, or if the carbon footprint requires calculating again, click the '**Clear**' button to eliminate the previous input. Click the '**Return**' button to switch to the last group of measured products.

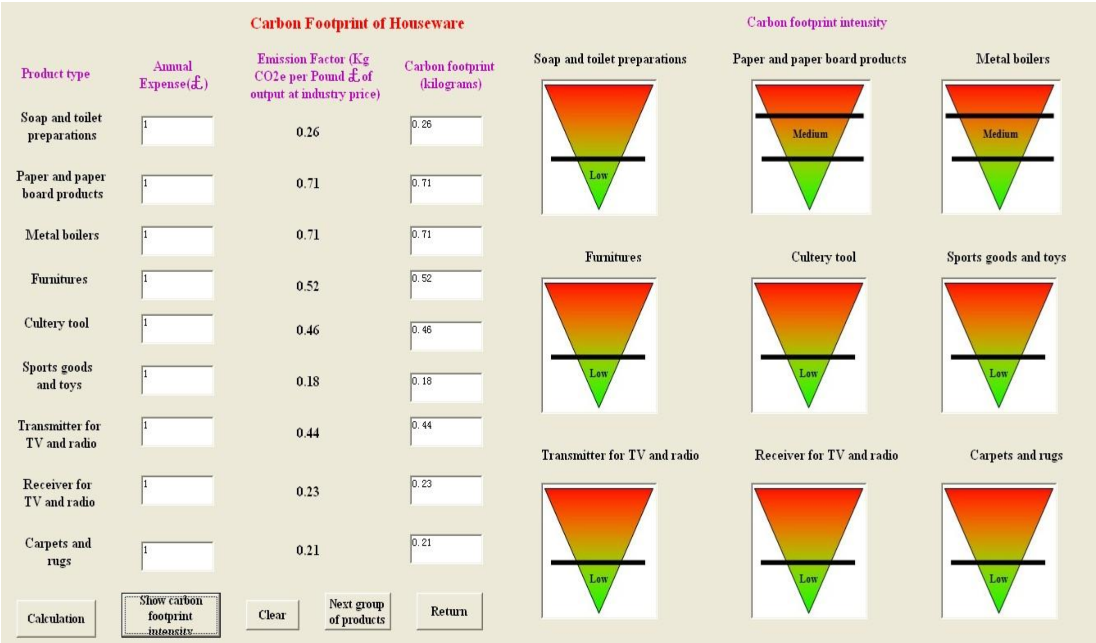


Fig.A.2.7. Carbon footprint and its intensity of selected household products (Form 1)

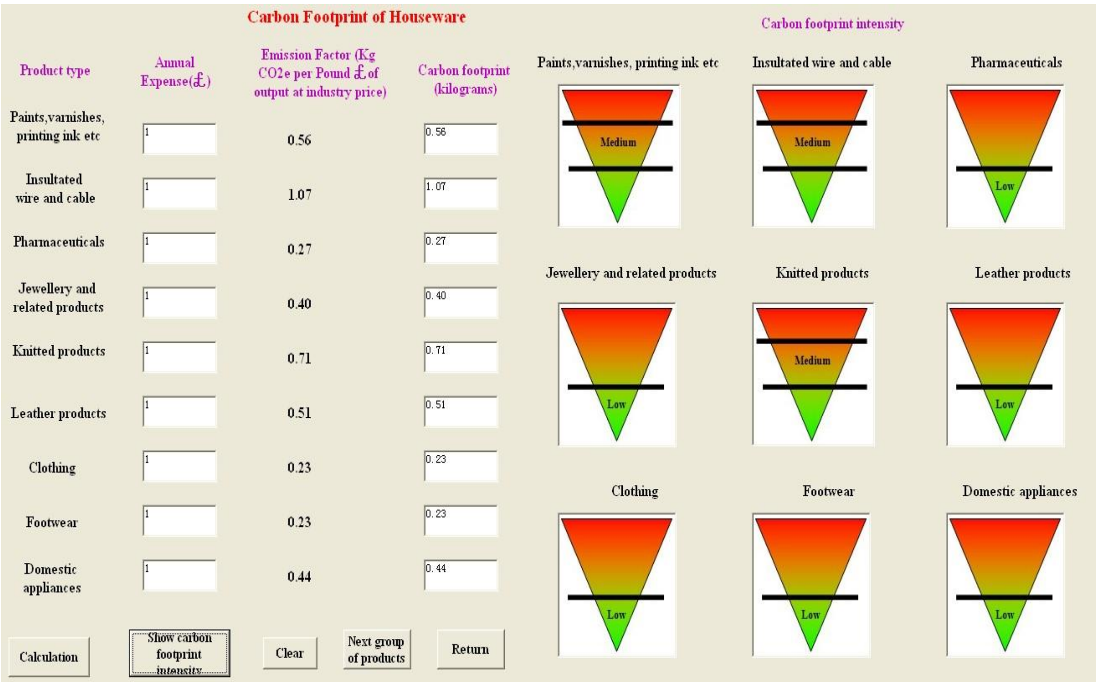


Fig.A.2.8. Carbon footprint and its intensity of selected household products (Form 2)

Once clicking the button '**Next group of products**', the form of carbon footprint measurement for 'other commercial products' is displayed, including chemicals, pesticides, fertilizers *etc*. While fill "1" in the annual expense box for each product, the corresponding carbon footprint in shown in the output box followed by '**Calculation**' clicking. If '**Show carbon footprint intensity**' is triggered, the intensity level for each product will be shown in the right side (See Fig.A.2.9). While escaping the functional module for products' carbon footprint measurement, click the '**Return to DSS**' button to go back to the main interface of the decision support tool.

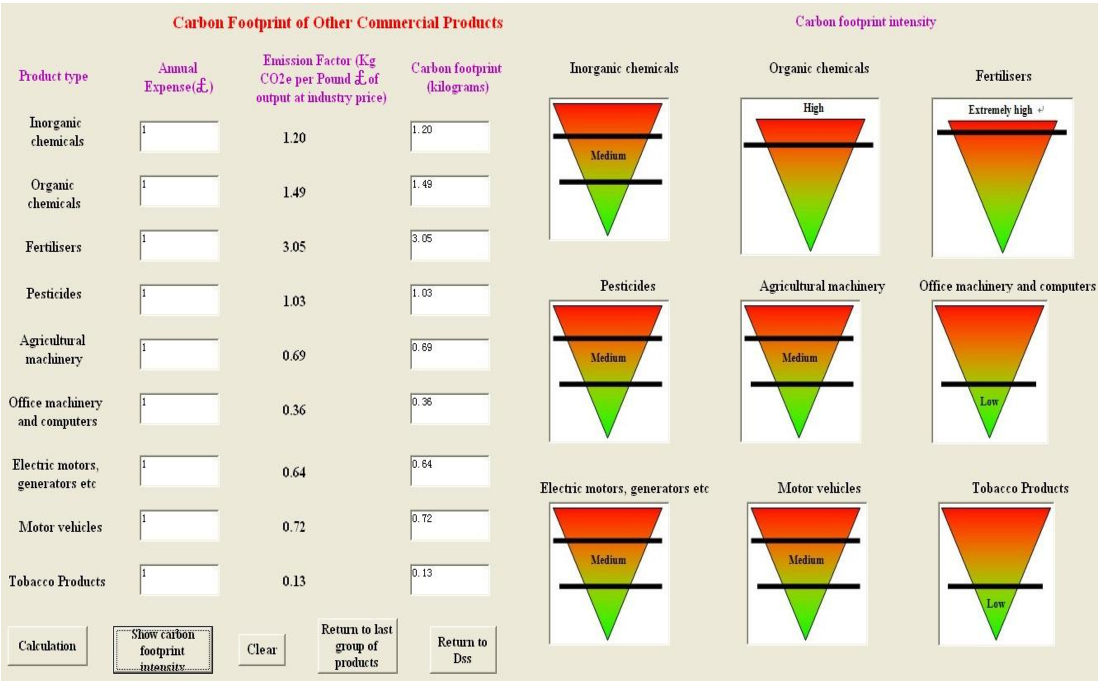


Fig.A.2.9. Carbon footprint and its intensity of 'other commercial product'

A.3 Gambit simulation

The 'Gambit' simulation tool is developed by Mckelvey *et al.* (2007, 2010), which is used to build and analyze certain extensive and strategic games (See Fig.A.3.1). Chapter 5 has employed 'Gambit' to simulate the created game model followed by a number of set scenarios, in which government and manufacturers' actions are discussed. In this section, a one-off game "Prisoner's Dilemma" will be simulated to demonstrate how to use this tool, in terms of the strategic game form.

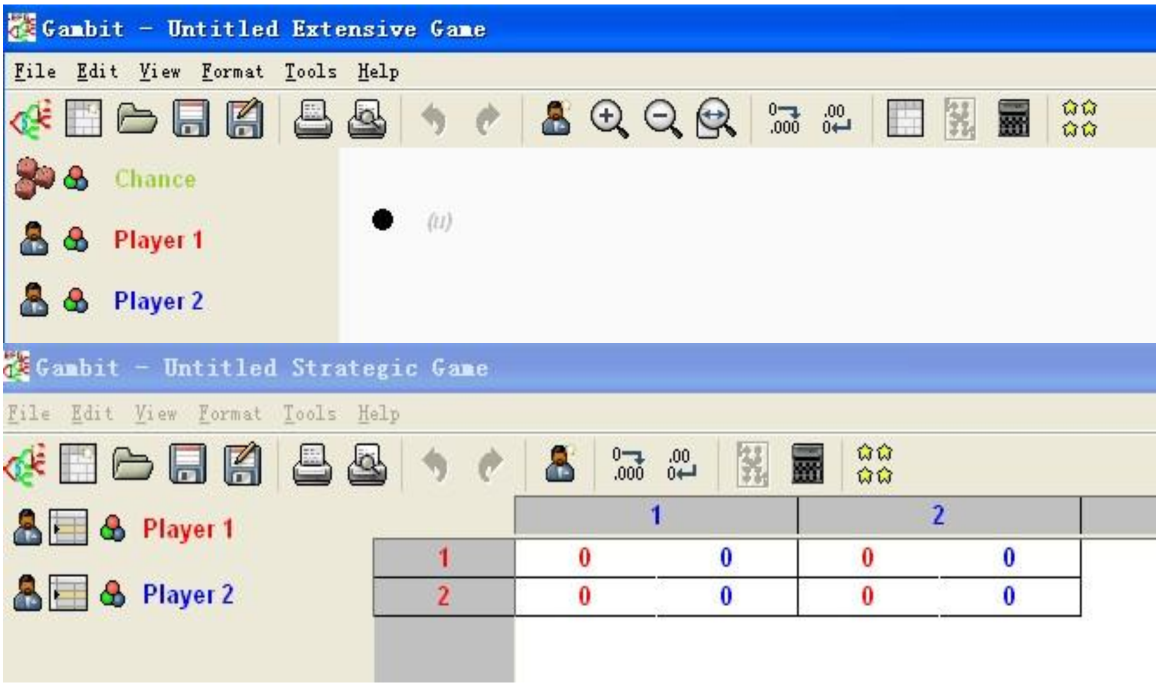
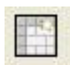


Fig.A.3.1. Screen shot the 'Gambit' tool

At first, select the icon of strategic game panel in the Gambit tool , and assume that there are two players who are called "Rui", "Gary" separately, as two prisoners involved in this game. Both of them have two strategies "not confess" and "confess" for determination, in which red color is represented for Rui's strategy and blue for Gary's. The payoff matrix of the above example "Prisoner's Dilemma" presented in Chapter 4, are used in this simple simulation. Fig.A.3.2 shows all the above information, ‘players’, ‘payoffs’ and ‘strategies’ are input the ‘Gambit’ tool.

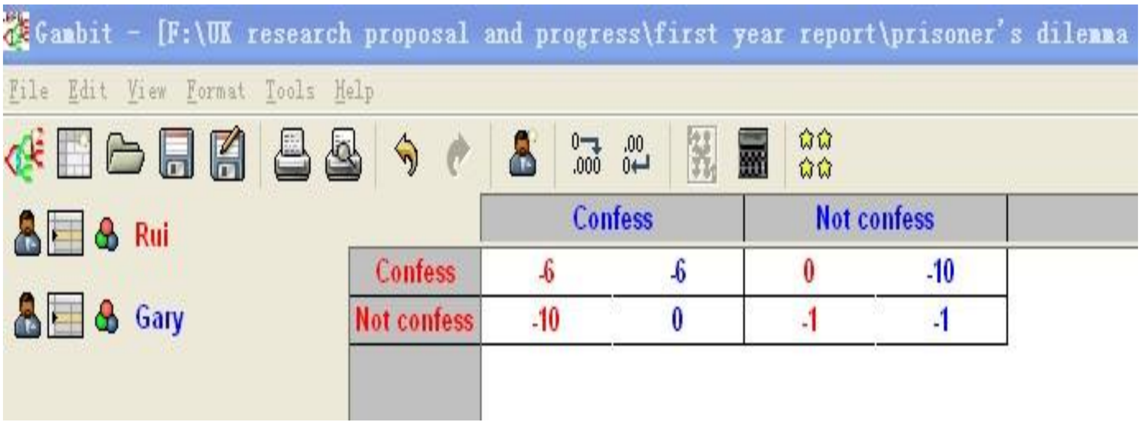


Fig.A.3.2. Payoff matrix of the “Prisoner’s dilemma”

It is considered that the game is enumerated the result with Rui’s strategic action at first (red colour), then by Gary’s strategic action (blue colour). Thus, the payoffs matrix can be displayed in Fig.A.3.3, by dragging the player icon  from the left of Gary’s name in the list of players and dropping it on the right side of Rui’s strategy label column.

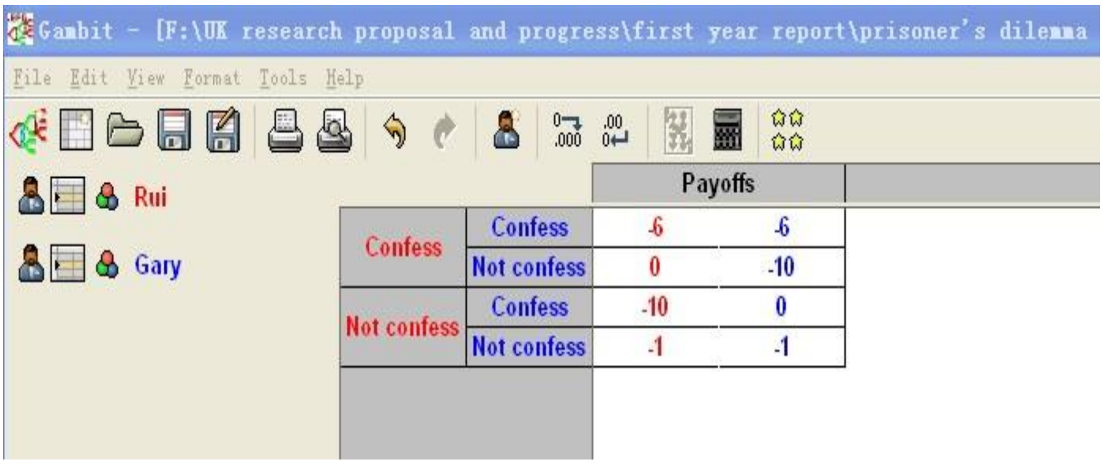


Fig A.3.3. “Prisoner’s dilemma” with Rui’s choice first

Strategies that are strictly dominated can be eliminated iteratively by the 'dominance' panel, which is shown in the 'Tools' dropdown list. Here, the dominated action is defined by Gambit tool as the action which shows always worse than another, regardless of beliefs at the information set (Mckelvey, *et al.*, 2010). In this game, the strategy of 'not confess' is strictly dominated by both players. Therefore, confess as the dominated strategy is labelled with "X" cross for both two players Rui and Gary. In addition, their corresponding payoffs are also marked with "X" cross. Fig.A.3.4 shows that all the dominated strategy for both players is crossed out.

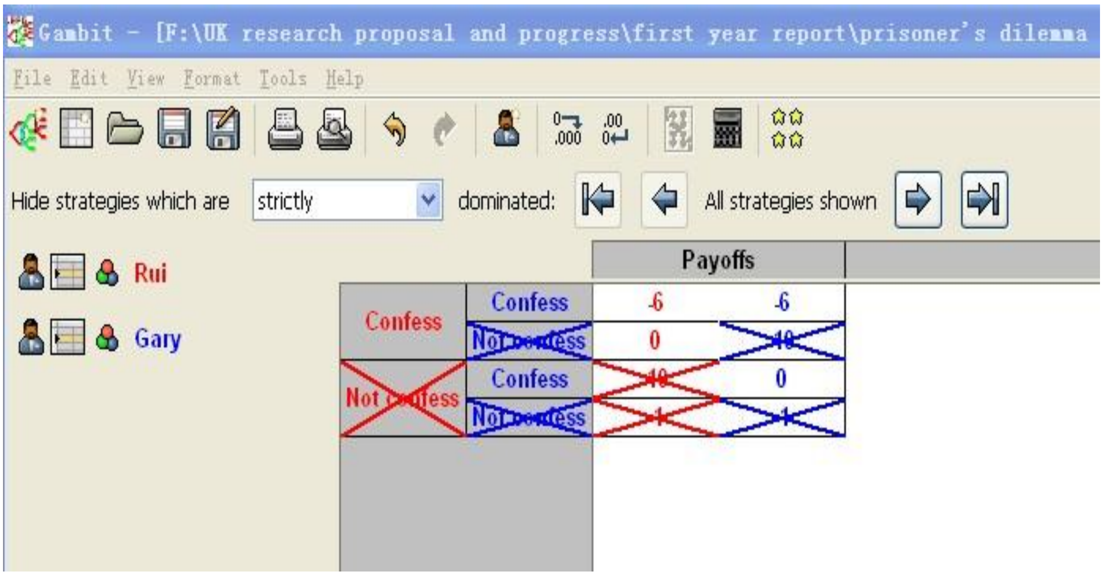


Fig.A.3.4. Dominated strategy crossed out

With the dominated strategy being crossed out, Fig.A.3.5 suggests that the optimal strategy for both prisoners is to confess by clicking the icon . The reason for this situation results from the dominant strategies determination. A dominant strategy is the best strategy for a player to adopt in a game no matter what strategies will be chosen by the other players (Mankiw, 1998). Since Rui's choice should be considered first, to confess is his dominant strategy regardless of whether Gary would confess or not. The reason is that if Rui decides to confess, he will spend less time in the prison maybe released or sentenced six year. On the contrary, if Rui does not confess, he may be suffered harsh sentence as ten years with greater probability by the reason that he is not sure whether Gary would cooperate with him as not confess for his initial determination. Similarly, Gary faces the same situation like Rui, and he would probably choose the same way. Gary may prefer confessing rather than confessing. Consequently, to confess is also a dominant strategy for Gary.

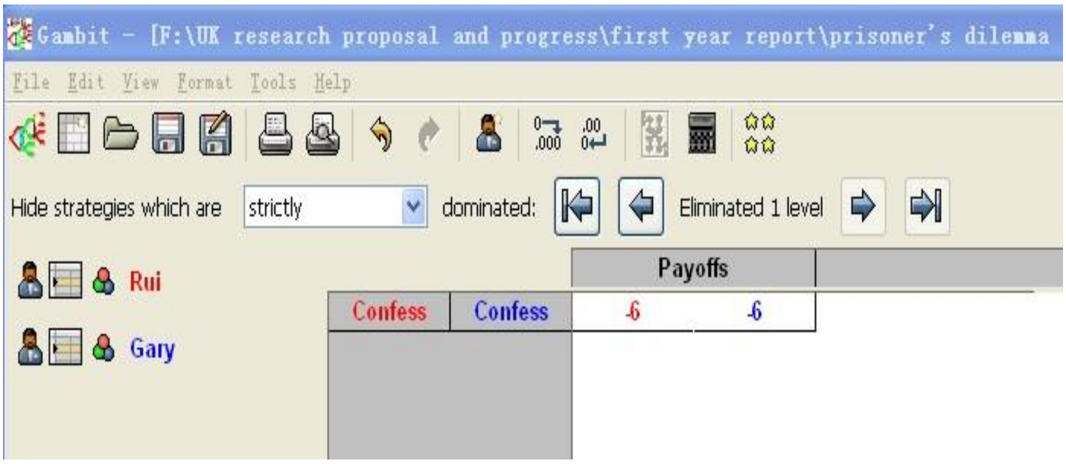


Fig.A.3.5. Dominant strategy for “Prisoner’s dilemma”

Accordingly, the Nash Equilibrium can be computed by clicking the icon , whilst a dialog box is coming out (See Fig.A.3.6). In this study, all the Nash Equilibrium should be calculated by the Gambit’s recommended method. While clicking the “OK” button, the computation result is shown in Fig.A.3.7. This result also suggests a pure strategy, which is a game with probability of one given to the selected strategy and zero to others (Romp, 1997), with the probability of one being calculated for strategy ‘confess’.

Fig.A.3.6. Nash Equilibrium computation

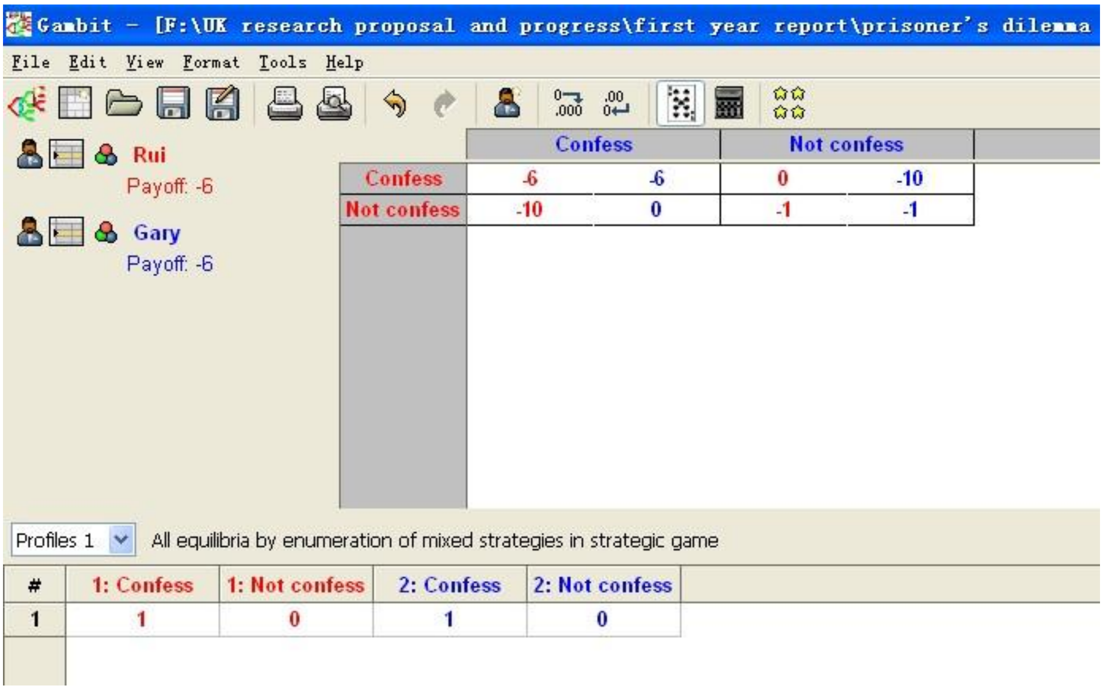


Fig.A.3.7. Nash Equilibrium computation result

The 'Gambit' tool also provides a novel approach called 'Quantal Response Equilibrium' (QRE) to search the subset of Nash equilibria by means of selection the 'QRE' from the 'Tools' dropdown list. This approach uses imperfect or noisy expectations logic instead of the perfectly rational expectations logic, when searching for the Nash Equilibrium (McKelvey and PalFrey, 1995).

Fig.A.3.8 shows how the 'QRE' approach is used to search Nash Equilibrium. As the QRE model is a function of probability distribution and the error of choice selection, Lambda (λ) in the figure is related to the level of error in expectation. For $\lambda = 0$, the actions are composed of errors, and for $\lambda \to \infty$, there is no error. If both players, government and manufacturers, evaluate their expected payoffs in an unbiased way, the probabilities of each strategy being selected should be the same at the beginning of the game, that is why all the graphs in Fig.A.3.8 start at 0.5. As Lambda tends to infinity (∞), the Nash Equilibrium converges to a unique value. For example in this game example, the pair of Nash Equilibrium is 'confess-confess'.

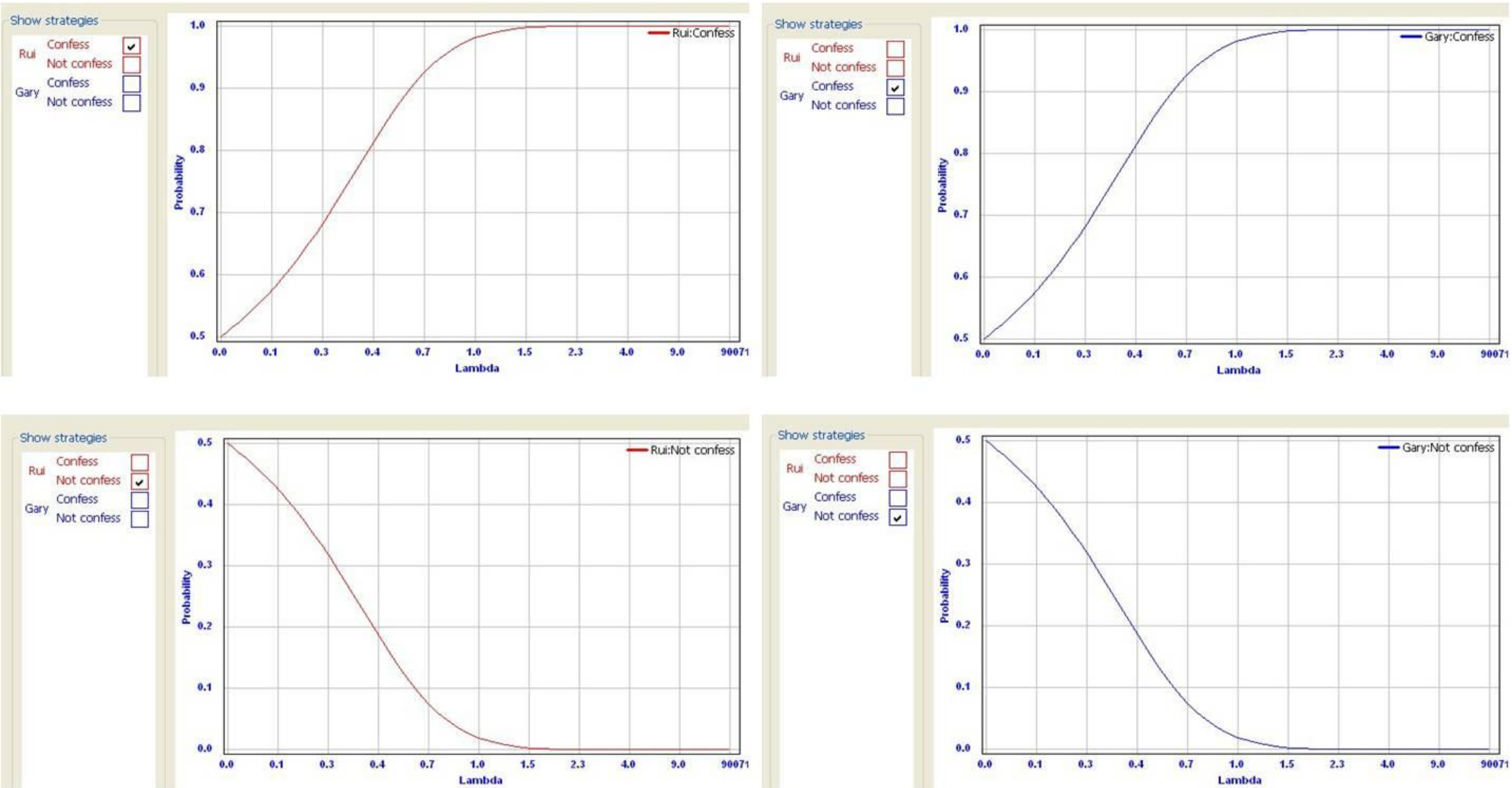


Fig.A.3.8. Quantal response equilibrium approach for “Prisoner’s dilemma”

A.4 Two players' game for decision making

This module is designed based upon 'Two-Person Non-cooperative Game Theory', which is mainly used in the Chapter 7. Game theory can be understood as an insightful tool to understand the possible relationships of cooperation or competition, whilst decision makers taking different actions (Rasmusen, 2007). In particular, game theory provides the perspective for business managers or those who interact with management to find out optimal strategies achieving commercial sustainability, as well as better understand the nature of incentives, conflict on decision making and how strategic actions affect the short or long term business (Kelly, 2003; Geckil and Anderson, 2010). There are three important factors being considered by game theory for decision making, as 'players', 'actions', 'payoffs' separately (see Fig.A.4.1).

Fig.A.4.1. Screenshot of the 'two players game for decision making'

‘Players’ in a game can be deemed as the individuals who make decisions (Romp, 1995). At least two players should be involved in the game situation, since that this functional module is based upon ‘two players’ game’. Furthermore, player can be considered as a general entity, *i.e.* a manufacturer, corporation, nation *etc* (Straffin, 1993). In some special cases, player can be also seen as a ‘Pseudo-player’, such as weather, economic situation (depression), *etc* (Rasmusen, 2007). ‘Action’ is similar to strategy, which presents how a player can move in a game situation. For instance, a player’s actions can depend upon the observation of other players’ movement in the game (Romp, 1995; Rasmusen, 2007). Once the potential actions have been determined in the game, different pay-offs will be generated accordingly and represented in the form of matrix. The payoffs can be related to the monetary value, *i.e.* economic profits, or the utility that players received in the game (Romp, 1995). In addition, it is assumed each player is rational in the game, whose action only cares about self-interest.

As a simple case to demonstrate how to use this functional module, two players have been defined as ‘Manufacturer’ and ‘Customer’, respectively, and suppose each of them has two available actions to lead their further action. For Manufacturer, the possible actions are: {SN, SO} which indicate that whether manufacturer will sell the new products (SN) or sell the old products (SO). The biggest difference between the new and old products is that the new one has taken environmental indicators into account, by means of reducing the inherent risk and associated carbon footprint to make products be more environmentally friendly. Correspondingly, there are two strategies for customers which are {WB, UWB}. Action WB means that customers are willing to buy the products no matter whether the products are environmental friendly, as well as NWB indicates the contrary consuming behaviour that customers are unwilling to buy both of these two products (See Fig.A.4.2).

Fig.A.4.2. Example game situation between Manufacturer and Customer

Payoffs corresponding to the actions can be input as the real monetary value or any logic unit. With the payoffs being adjusted, the game solution can be varied accordingly. For example in the above example, the payoffs are determined by the potential economic profits, compared with the cost which is quantified by 1 unit. Fig.A.4.3 shows the simplest case is that Manufacturer will gain 3 units whilst consumers favouring the new environmental friendly products, as well as Customer can save 20% in comparison with the Recommended Retail Price (RRP). However, Manufacturer will lose 1.5 units if Customers are not interested in the new products and thus unwilling to buy. With regard to the old products sell, Manufacturer can gain 2.5 units once customer has decided to purchase, whist saving 35% for customer. Moreover, only 0.5 units will be lost if customer is unwilling to buy the old products. No matter Consumer takes actions on not buying new or old products, no economic saving will be generated as the payoff is 0.

Fig.A.4.3. Payoffs for different actions

Once all the payoffs have been determined in the game situation, dominant strategy can be found by means of clicking the button of 'Solution'. A dominant strategy is defined as the optimal strategy for a player no matter what the other player chooses (Geckil and Anderson, 2010). The example shows the solution is that both players choose action 1, which is the unique dominant strategy of the game. In this case, Manufacturer will provide new environmental soundly products for the market, as well as customers are willing to buy (see Fig.A.4.4). If other payoffs need to be modified, or if another game situation is proposed to resolve, click the 'Clear' button to eliminate the previous input and determine new numerical value for 'Players', 'Actions' and 'Payoffs'. When escaping this functional module, click the ‘Return’ button to return the main interface of the decision support tool.

Fig.A.4.4. Solution of the example game

A.5 Environmental impact assessment

This functional module is mainly used in both Chapter 6 and Chapter 7 for carbon footprint measurement in the supply chain network. There are three stages being considered, as production, transportation and waste disposal. The approach for carbon footprint measurement is developed by Department for Environment Food and Rural Affairs (DEFRA), to apply green house gases emission factor multiplied by activity data. Activity data of supply chain network mainly reflect the energy consumption in the process of production and transportation, amount of waste production *etc*. The corresponding greenhouse emission factors are derived from the DEFRA GHG

Conversion Factors Guidelines (2009). However, this is a simplified approach for carbon footprint measurement, which only takes the direct energy consumption into account. Once clicking the button ‘Environmental Impact Assessment’ from the interface of the decision support tool, the first stage as “Direct Energy Consumption in the Industrial Processes and Product Use” is displayed (see Fig.A.5.1).

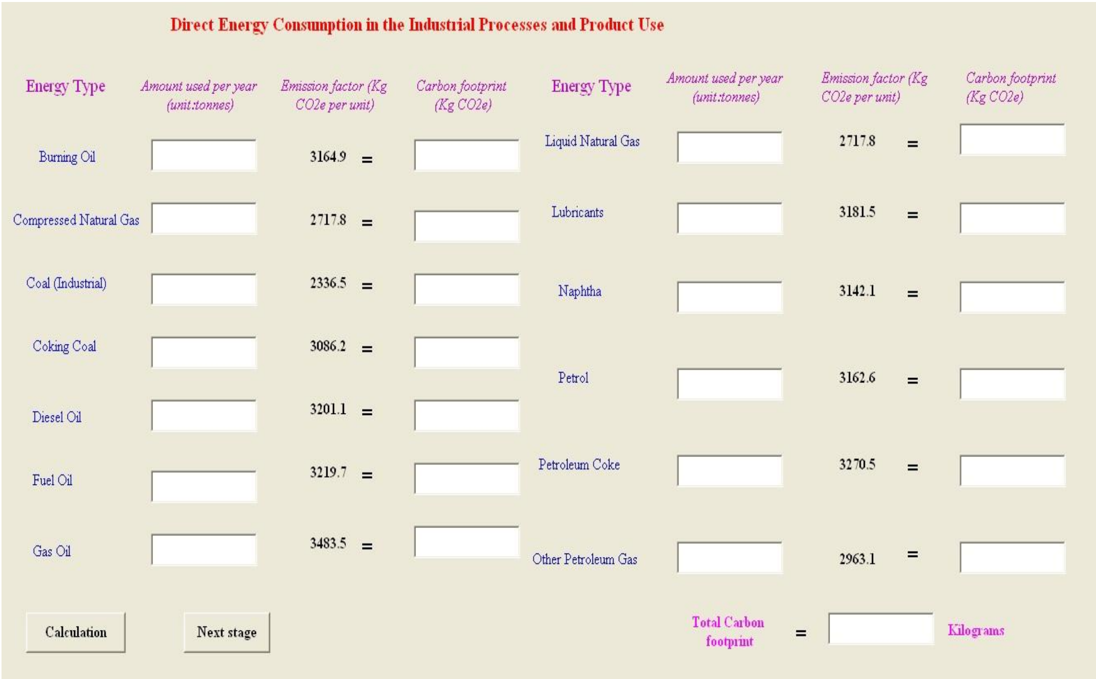


Fig.A.5.1. Direct Energy Consumption in the Industrial Processes and Product Use

All the energy consumptions are measured annually by using the unit of ‘tonne’, and the carbon footprint is measured by ‘Kilogram’. There are two buttons at the left corner, ‘**Calculation**’ and ‘**Next stage**’, respectively. When all the information of annual energy consumption submitted by means of the ‘**Calculation**’ button, the carbon footprint of each kind of energy can be produced in the corresponding blank boxes and the total carbon footprint will show in the right corner. Once finishing the calculation, click ‘**Next stage**’ to move to the transportation stage.

In order to measure the carbon footprint during the product transportation, four common used fuels have been considered, petrol, diesel, liquid petroleum gas (LPG) and compressed natural gas (CNG) (See Fig.A.5.2). However, their measure units are slightly different, as the former three use ‘litre’, whilst the latter one uses ‘kilogram’. Once inputting the annual using amounts for each type of fuel, the corresponding carbon footprint and the total carbon footprint of the transportation stage can be calculated by clicking the button ‘**Calculation**’. If the carbon footprint in the process industrial production wants to be reviewed, click the button ‘**Return to the above stage**’ to return. Conversely, click ‘**Next stage**’ and move to the waste disposal stage.

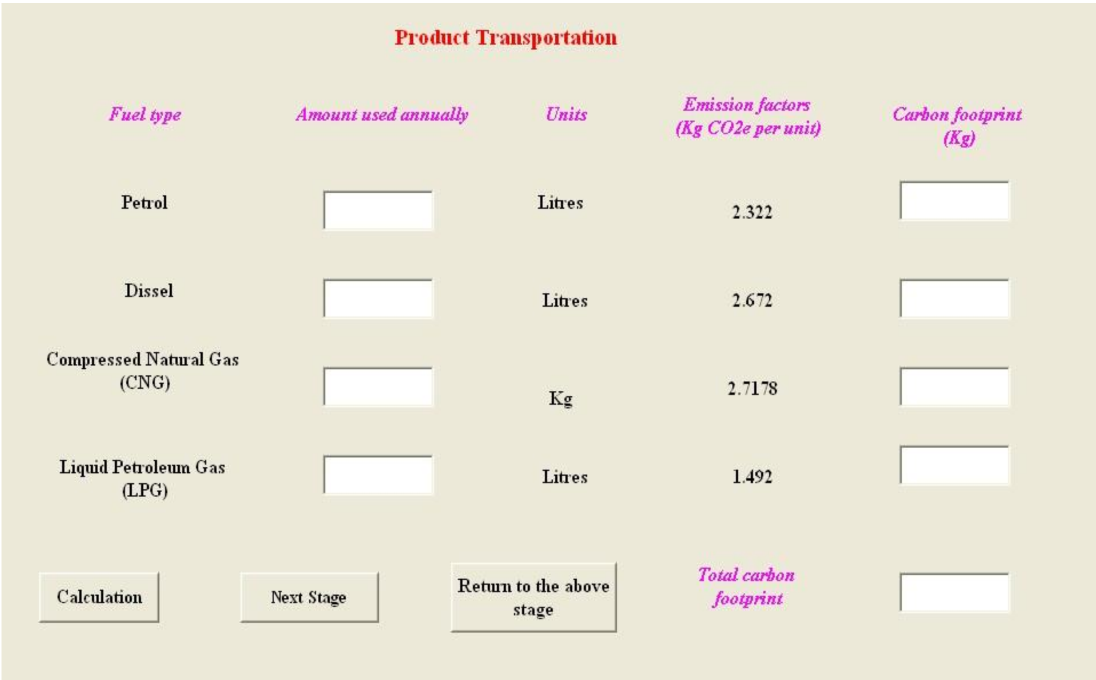


Fig.A.5.2. Carbon footprint measurement in the transportation stage

Fig.A.5.3 shows that 16 types of waste materials are considered to measure their carbon footprint in the stage of final disposal, such as paper and card, wood, textiles, glass, tyres *etc*. When the information of annual waste production is input, the corresponding carbon footprint can be output. Similar to the transportation stage, If the carbon footprint in the process of production and transportation want to be reviewed, click the button '**Return to the above stage**' to return. Moreover, the summary information for the three measured stages has been provided followed by clicking the button '**See summary**'.

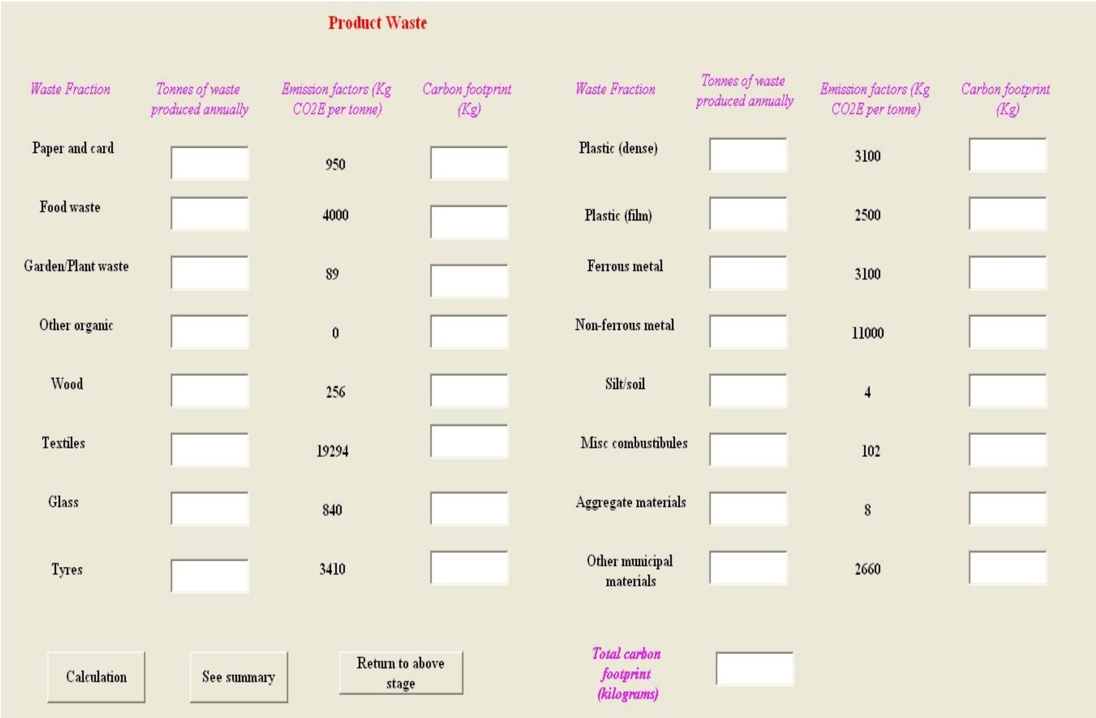


Fig.A.5.3. Carbon footprint of different waste materials

In the summary section, the carbon footprints calculated for the three stages (Production, Transportation and Disposal) are listed sequentially. While clicking the button '**Total carbon footprint**', the carbon footprint of the whole supply chain network can be measured roughly by combining the carbon footprint at each stage together. Click the '**Quit**' button to escape this functional module, and return to the main interface of the decision support tool (See Fig.A.5.4).

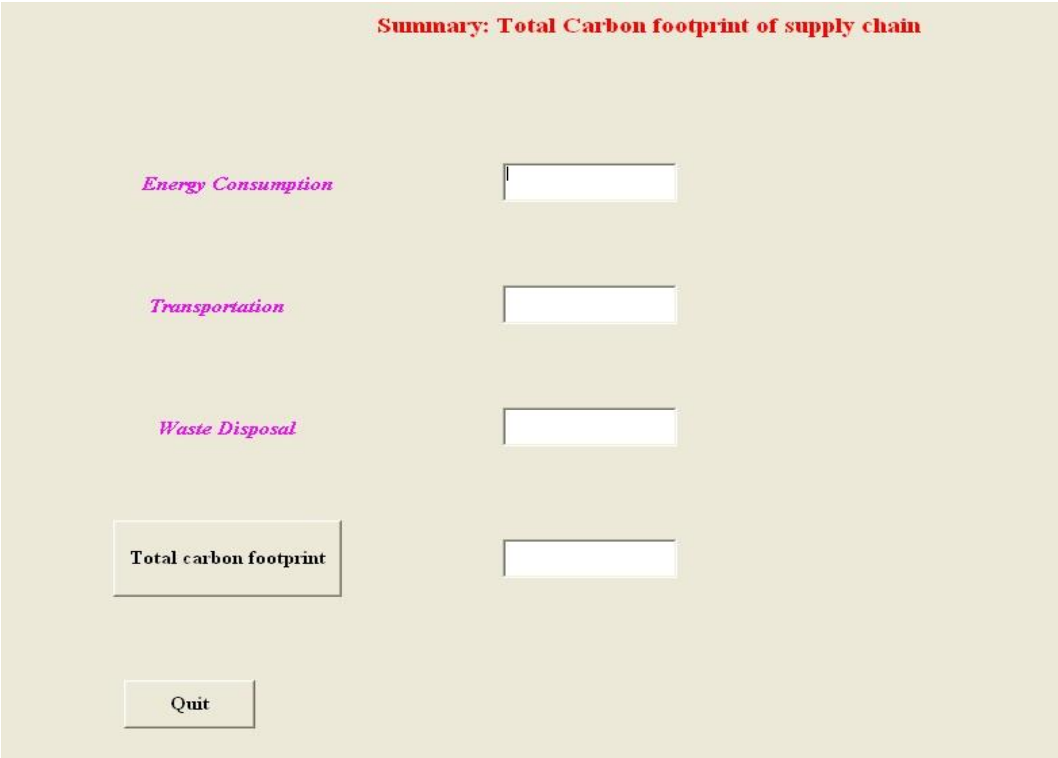


Fig.A.5.4. Summary of total carbon footprint in the supply chain

A.6 Materials selection for cleaner industrial production

In order to help the engineer or designer employ the grey analysis more conveniently, as well as simplify the computation complexity, this approach has been embodied into a computational tool based on a spreadsheet (Microsoft Excel 2007). This functional module has been divided into two modules, representing the input parameters and the output of the analysis results.

As the 'Scirus' case example has been presented in Chapter 8 in terms of the screenshots, following illustration is using the weighting value assigned by the product manager of the cited handbag manufacturer. Fig.A.6.1 depicts the input module of the developed tool, starting with the weighting value determination by marking 1, 0 or 0.5 in the designed ‘binary-dominance matrix’ table. Then, enter the numerical value for each indicator derived from the case example, shown in Fig.A.6.2.

When all the information has been submitted, the evaluation result of the case example can be calculated by means of the spreadsheet programming, and a sequence of the evaluated materials can be ranked from the highest to the lowest grade, shown in Fig.A.6.3. Thus, material E is the most ‘environmentally friendly’ material among the five PVC materials, with material A the least.

First step: weight determination		Energy consumption %	Human health risk/toxity	Materials Recyclability %	Materials Reusability %	Use of recycled materials %	Manufacture defects %	Defects recyclability %	By-products %	By-products recyclability %	Waste production %	Manufacture cost %	Sales profit %	Total Score	Weight Value
1	Energy consumption %		1	0	0	1	1	1	1	1	0	0	0	7	0.088607595
2	Human health risk/toxity	1		1	1	1	1	1	1	1	1	0	1	11	0.139240506
3	Materials Recyclability %	1	0		0.5	1	1	1	1	1	0.5	0	0	8	0.101265823
4	Materials Reusability %	1	0	0.5		1	1	1	1	1	0.5	0	0	8	0.101265823
5	Use of recycled materials %	0	0	0	0		0	0.5	0	0.5	0	0	0	2	0.025316456
6	Manufacture defects %	0	0	0	0	1		1	0.5	1	0	0	0	4.5	0.056962025
7	Defects recyclability %	0	0	0	0	0.5	0		0	0.5	0	0	0	2	0.025316456
8	By-products %	0	0	0	0	1	0.5	1		1	0	0	0	4.5	0.056962025
9	By-products recyclability %	0	0	0	0	0.5	0	0.5	0		0	0	0	2	0.025316456
10	Waste production %	1	0	0.5	0.5	1	1	1	1	1		0	0	8	0.101265823
11	Manufacture cost %	1	1	1	1	1	1	1	1	1	1		1	12	0.151898734
12	Sales profit %	1	0	1	1	1	1	1	1	1	1	0		10	0.126582278

Fig.A.6.1. Weighting value determination for each indicator

Second step: Parameters Determination		Input name: **Material A**	Input name: **Material B**	Input name: **Material C**	Input name: **Material D**	Input name: **Material E**	**Ideal Parameters**
1	Energy consumption %	97	93.6	89.5	83	80	70
2	Human health risk/toxity	0.0015	0.0013	0.0005	0.0007	0.0002	0.0001
3	Materials Recyclability %	94.7	95.3	94	96.3	98	98
4	Materials Reuseability %	0.13	0.16	0.22	0.11	0.23	0.23
5	Use of recycled materials %	90.8	91	91.9	92.7	92	93
6	Manufacture defects %	8.1	7.3	5.8	6	5	2
7	Defects recyclability %	90	93	93.6	89	94	95
8	By-products %	0.02	0.017	0.013	0.013	0.011	0.011
9	By-products recyclability %	0.12	0.14	0.16	0.1	0.2	0.2
10	Waste production %	4.9	4.5	3.6	2.9	2.5	2
11	Mannufacture cost %	42	38	32	34	28	30
12	Sales profit %	40	39.8	38.6	35.7	31	45

Fig.A.6.2. Numerical values input for each indicator

Evaluation Result Analysis (Degree of Grey Incidence R_i)		Material A	Material B	Material C	Material D	Material E
1	R_A	0. 768372904				
2	R_B		0. 795951033			
3	R_C			0. 836494293		
4	R_D				0. 830072357	
5	R_E					0. 860786592

Fig.A.6.3. Grey evaluation result of the case example

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Appendix B: List of Conferences

[1] Zhao, R., Neighbour, G., Han, J. and Deutz, P., 2010. Application of Game Theory to Supply Chain Network of Hazardous Materials: Environmental Risk and Carbon Footprint. Summer Symposium on Sustainable Systems (4S), Sannäs, Finland, 15th-17th, June, 2010. (Oral and poster presentation)

[2] Zhao, R., Neighbour, G., Deutz, P. and Han, J., 2010. Clean Production: A Game between Government and Manufacturers? UK Chinese Association of Resource and Environment Annual Meeting, University College London, 11th September 2010. ISBN: 9780955196553. (Invited oral presentation)

[3] Zhao, R., Neighbour, G., Deutz, P., 2011. Preliminary Study of Hazardous Materials Management: An Optimization Model in the Context of Green Supply Chain Management. IEEE Proceedings of the 2011 5th International Conference on Bioinformatics and Biomedical Engineering. (EI and ISTP Indexed) (Oral presentation)

[4] Zhao, R., Neighbour, G., Deutz, P., Selection of Carbon Materials for Cleaner Industrial Production: An Environmental Evaluation Approach. Proceedings of World Carbon Conference 2011, Shanghai, 24th-29th, July, 2011 (Keynote Speech)

[5] Zhao, R., Deutz, P., McGuire, M., Environmentally Friendly Products: A Game between Manufacturers and Consumers? 18th Annual International Sustainable Development Research Conference, University of Hull, UK, 24th-26th, June, 2012. (Oral presentation)

Appendix C: List of Journal Papers

[1] Zhao, R., Deutz, P., Neighbour, G., McGuire, M. Carbon Footprint Intensity: an Indicator for Improved Carbon Labelling Scheme. 2012. Environmental Research Letters 7, 01414. (Impact factor: 3.631).

[2] Zhao, R., Neighbour, G., Deutz, P., McGuire, M., Materials Selection for Cleaner Production: An Environmental Evaluation Approach. 2012. Materials & Design 37, 429-434. (Impact factor: 2.200).

[3] Zhao, R., Neighbour, G., Han, J.J., McGuire, M., Deutz, P., Game Theory Approach to Strategy Selection for Environmental Risk and Carbon Footprint Reduction in the Green Supply Chain. Journal of Loss Prevention in the Process Industries (Impact factor: 0.913). In press (http://dx.doi.org/10.1016/j.jlp.2012.05.004)

[4] Zhao, R., Neighbour, G., Deutz, P., McGuire, M., A Computer Based Game Theory Simulation for Cleaner Production: An Interplay between Manufacturers and Government. Submitted to Journal of Loss Prevention in the Process Industries (Impact factor: 0.913), Under Review.