DEFINING A COMPREHENSIVE METHODOLOGY FOR SUSTAINABILITY ASSESSMENT OF MEGA-EVENT PROJECTS

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Посвящается моим дорогим родителям

To my dearest parents

Abstract.

Mega-event projects such as the Olympic Games or FIFA World Cup are unique large-scale projects that involve complex planning process, vast array of stakeholders and substantial capital investment. They attract global media attention and tourism to a host city. However, the success of a mega-event is not measured only in terms of its organisation and staging. It is crucial to create a sustainable positive post-event legacy because this is where the most of the long-term impacts will occur.

Planning of such projects is a complicated process that requires consideration of multiple economic, environmental and social aspects and the trade-offs between them. The main objective of this work is to develop a comprehensive framework that can assist decision makers with assessment of the alternative site design scenarios in order to identify the optimum solution. A case study based on the London Olympic Park is applied to test the feasibility of the proposed framework.

Stakeholders' engagement in a mega-event project planning is a prerequisite for its success. This work demonstrates how a multi-criteria decision analysis (MCDA) tool can be applied to analyse and quantify the views of different stakeholder groups and identify the design features which are considered the most important by the majority of stakeholders.

The environmental assessment framework includes a combination of computational models which evaluate and optimise the total emissions resulting from the transportation, materials, water and energy use, and a series of life cycle assessment (LCA) models which estimate environmental burdens resulting from municipal solid waste (MSW) treatment systems. The results of the assessment provide valuable information for the decision makers in terms of the amount of materials and energy used and related environmental burdens for each scenario. Optimisation models can determine 'the optimum' solution for each scenario which can serve as a performance benchmark during the planning process.

Declaration

I, Olga Parkes, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Signature…………………………………….

Date ………………………………………

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Chapter 1. Introduction.

This chapter first provides the definition of mega-event projects and explains their significance for the host cities. Then the challenges and complexities of sustainability assessment of mega-event projects are outlined. Next, the main aims and objectives of this work are presented and the research questions are specified. The final section provides the structure of the thesis defining the contents of each chapter.

1.1 Mega-event projects – urban development drivers.

Mega-events can be defined as 'events, which are so large in scale they have the ability to affect the host city or nations' whole economies and reverberate throughout the global media' (VisitScotland, 2012). These events involve significant capital investments, long-term planning and a large and varied set of stakeholders. The most well-known mega-events are the Olympic Games, FIFA World Cup and a World Fair such as the Expo events.

A mega-event normally results in numerous economic benefits for a host city such as the increased number of tourists, major investment in regeneration and infrastructure projects, income from tickets and licencing sales. Mega-events also generally entail social benefits such as new transport infrastructure in a host city, creation of thousands of new jobs during the construction and staging of the event, sport education and promotion amongst young people, etc. Mega-events are also associated with major environmental impacts, particularly during the construction phase, due to the vast amounts of construction materials, energy and water used, emissions from transportation, increased air and noise pollution, waste generation and many others. Therefore, the success of a mega-event cannot be measured only on the basis of its financial benefits; a holistic evaluation of a mega-event should include all aspects of sustainability – economic, environmental and social.

A mega-event as an overall project consists of the following main phases: construction, event and legacy. Thus, sustainable planning and evaluation of a mega-event project should not be focused only on the event itself but needs to address all phases. This is because the major use of the infrastructure built for a mega-event from a host city's perspective is the post-event phase. The time length of the actual event is merely a few weeks, which is almost irrelevant compared to the time length of the legacy phase measured in decades.

Mega-events projects are very important for policy-makers, local, national and international authorities, investors and the general public of a host city as they create long-lasting legacies for the host cities and surrounding communities. A legacy can be defined as the impact which occurs from hosting a mega-event, which can be both positive and negative. Positive legacies are those that create long-term positive impacts such as promotion of sport, attraction of tourism and investment, efficient utilisation of the event infrastructure in the post-event period. Negative legacies occur when the post-event site is abandoned, the eco-system and biodiversity of the site are damaged, the venues and infrastructure are not utilised and the local community does not benefit in any way from hosting the event. It is argued that negative legacies often occur because the post-event phase is regularly neglected in the planning and implementation processes (AngeZ, 2013). Thus, it is crucial that the post-event site redevelopment is included in the early planning process of a mega-event project.

Because of the high profile of a mega-event project and its significant effects on a host city, decision-makers must consider the overall long-term impacts of the whole project rather than short-term effects of the event organising and staging. It is crucial to integrate a post-event site as a sustainable part of a host city in order to secure long lasting positive legacies of a mega-event. Thus, a holistic system approach should be adopted when planning a mega-event which considers all phases and facilitates long-term benefits of the overall project.

1.2. Measuring sustainability performance of mega-event projects.

In the last few decades, the concept of sustainable development (SD) has become a fundamental part in the management strategies of most business and industrial enterprises, infrastructure projects and government policies (Heijungs et al., 2010). Sustainability concept was first incorporated into the bidding proposals for mega-events in the 1990s when the International Olympic Committee (IOC) reported that the candidate cities should be evaluated on the environmental consequences of their plans and pointed out the importance of sustainability assessment of the Olympics in terms of long-lasting legacy (Gold and Gold, 2011).

Nowadays, the organisers of mega-events have to develop sustainability strategies based on the national and international guidelines and standards, such as BS 8901 ‘Specification for a Sustainability Management System for Events’, ISO 20121 ‘Event sustainability management systems’, IOC ‘Guide on Sport, Environment, and Sustainable Development’ and others. The standards provide useful recommendations to the event organisers on the implementation of various measures to reduce environmental impacts associated with the event staging and organising. Although recommendations can be useful when developing a sustainability management strategy, they are mostly descriptive and do not specify which aspects to address, what performance levels to achieve and how to do so. They do not clarify how to monitor and report the performance and do not refer to the post-event phase. Hence, there is no universal standard that provides a specific methodology applicable for quantitative assessment of any mega-event.

Measuring sustainability performance of mega-event projects is a complex task. Each such project is unique because of its geographical location, design of the event site, venues and infrastructure, various practices and experiences of the host cities, different public-private alliances and many other factors. Thus, a set of performance indicators developed by the event organisers usually varies across different mega-event projects and normally includes a mix of qualitative and quantitative indicators which makes it hard to measure them systematically.

A critical review of the recent publications on sustainability assessment of mega-event projects (Chapter 3) identified a number of studies that presented different methodologies on quantifying the economic or environmental impacts of mega-events. Several studies address social impacts of mega-events; however, they mostly present qualitative frameworks. Most literature addresses the event and construction phases and generally mentions post-event phase only in terms of tourism and sports legacies. The analysis highlighted that there is no a standard methodology that is applicable for a comprehensive quantitative sustainability assessment of mega-event projects which is also confirmed by other researchers (e.g. Collins et al., 2009).

Therefore, I identified the need for a holistic quantitative methodology that can assist decision-makers with planning of a mega-event project. This methodology is necessary in order to evaluate the impacts of all phases of the project and examine how negative impacts can be minimised and the overall performance can be optimised. Thus, the methodology can provide decision makers with valuable information crucial during planning for the best design scenario.

1.3. Aims and objectives of the project.

In this work I present a novel comprehensive framework for sustainability assessment of mega-event projects. The major focus of the framework is on the stakeholders' engagement in the planning process and a holistic economic, environmental and social assessment of all stages of a mega-event project with particular emphasis on the legacy phase. It is a top-level strategic impact assessment tool that can be used by the decision makers and planners throughout the whole project's life cycle for the evaluation and optimisation of the proposed design scenarios.

Although all three pillars of sustainability have to be addressed for a complete evaluation, the main objective of this work is the environmental and social assessment of mega-event projects with a special focus on the legacy phase. Economic evaluation of mega-events has been carried out a number of times (e.g. Preuss, 2004). However, there are still many issues that still remain uncertain and require input of economists. Therefore, economic assessment is beyond the scope of this project.

The following questions are addressed in this work:

- What is the most suitable set of key indicators and tools applicable for the holistic assessment of mega-event projects?
- Where do the highest environmental impacts occur at each project phase?

- How to optimise the environmental impacts resulting from the transportation and the use of energy, resources and construction materials?
- What is the optimum long-term waste management strategy for the post-event site?
- How do we quantify social aspects of the proposed site design scenarios?
- How do we incorporate the views of all stakeholders into the planning of mega-event projects?

The last two questions address social aspects of sustainability.

In order to demonstrate how a proposed framework can be used as a decision support tool during the planning of mega-event projects, it was applied to a case study – the London Olympic Park. Three potential post-event site design scenarios have been developed to test the practicality of the proposed framework.

The environmental assessment is carried out using a set of optimisation models for the evaluation of greenhouse gas (GHG) emissions resulting from the transportation, materials, energy and water use, and a set of life cycle assessment (LCA) models for the evaluation of the environmental impacts of the proposed waste treatment options. The summary of the results presents valuable information regarding the emissions associated with energy and resource usage which can be used during the planning process for the evaluation of the proposed scenarios and optimisation of their environmental performance. Other environmental issues such as biodiversity and land degradation also have to be considered during the planning of mega-event projects. However, due to the lack of scientific expertise necessary for a complete examination of these complex issues they are not considered in this work. Due to the lack of data on other emissions (e.g. those resulting in ozone layer depletion or acidification) only GHG emissions are considered in the optimisation models.

Mega-event projects have multiple short- and long-term impacts on different groups of stakeholders. In turn, stakeholders can also greatly influence the success of a mega-event and, therefore, must take part in the planning process. Various groups of stakeholders may have different, often conflicting views on the same issues. In this work I demonstrated how multi-criteria decision analysis (MCDA) can be applied to analyse and quantify the views of stakeholders. The results of the MCDA provide the insights on the viewpoint of each group of actors and help to determine those aspects that are considered the most significant by the majority of stakeholders.

Full social impact assessment requires participation of social scientists and, therefore, is beyond the scope of this work.

1.4. Thesis outline.

This thesis consists of eight chapters. The introduction begins with the definition of a mega-event project and its significance for a host city. Then it outlines the challenges of sustainability assessment of mega-event projects followed by the aims and objectives of this work. Chapter 2 provides a critical analysis of the sustainability assessment indicators and tools commonly used in the current practice, their types, characteristics and purposes. Chapter 3 investigates a number of studies that address sustainability assessment of mega-events. Chapter 4 presents a proposed novel comprehensive methodology for sustainability assessment of mega-event projects, summarises the assessment tools and outlines the case study – the London Olympic Park. Chapter 5 demonstrates how MCDA technique is applied for analysing and quantifying the views of different stockholders. Chapter 6 presents the description, mathematical formulation and results of the optimisation models developed in this work to evaluate and optimise GHG emissions resulting from transportation, materials, energy and water use. Chapter 7 provides the results of the environmental impact assessment of the integrated waste management scenarios which was carried out using LCA tool. Finally, Chapter 8 presents the main conclusions drawn from this work and provides the recommendations for future work.

Chapter 2. Sustainability assessment: complexities, measurements and recent developments.

This chapter provides an overview of the recent studies on various aspects of sustainability assessment. It starts with the definition of sustainability indicators and description of various indicator types. Then it explores the development of sustainability indices and frameworks. The next part provides a critical review of numerous evaluation tools and techniques used in the current practice. The main findings are outlined in the summary.

2.1. The definitions and history of sustainability indicators.

Indicators have long been accepted as valuable tools for communicating complex processes, events or trends to a broad audience. The term "indicator" originates from the Latin verb "indicare", which means "to proclaim or to point out" (Macgillivray and Zadek, 1995).

The term 'indicator' is defined in different ways. The Organisation for Economic Co-operation and Development (OECD) (OECD, 1994) states that an indicator is "a parameter or a value derived from parameters, which provides information about a phenomenon. The indicator has significance that extends beyond the properties directly associated with the parameter values. Indicators possess a synthetic meaning and are developed for a specific purpose". Huang *et al*. (1998) describe indicators as pieces of information that disclose the condition of large systems and Afgan *et al*. (2000) state that indicators are the quantifying factors for the comparison between various states or structures of the system. Mayer (2008) defines indicators as variables that express one attribute of the state of a system, normally through experimental or estimated data. Macgillivray and Zadek (1995) state that indicators usually simplify and quantify complex events to enable or promote communication. The above definitions show that the main purpose of an indicator is to communicate complex information to a wide range of actors in a simplified manner suitable for decision-making purposes.

The development and use of the indicators to communicate information about sustainability started many decades ago. First, the indicators that addressed the economic, social and environmental progress on the national level started to emerge, followed by the development of local-level indicators and Local Agendas 21 (LA 21) after the World Sustainable Development Summit in Rio in 1992, as well as corporate- and industry specific-level indicator sets. Macgillivray and Zadek (1995) state that first economic indicators emerged after the standardisation of the system of national accounts (SNA) in 1947, and the Gross National Product (GNP, later Gross Domestic Product or GDP) was adopted as a major indicator of the economic progress. For a long time GDP has been the major indicator of economic development. It has been widely used by economists, policy makers and international agencies as a main scorecard of a nation's economic wealth and well-being.

It is argued, however, that while GDP is a good economic indicator, it is inadequate as a sustainability indicator (Perdan and Azapagic, 2011). GDP is a gross sum of products and services bought and sold, which does not differentiate transactions that improve well-being from the ones that reduce it. GDP assumes that all monetary transactions add to social well-being without distinguishing costs from benefits, productive economic activities from destructive ones, or sustainable from unsustainable ones. For example, unnecessary spending due to preventable natural disasters, crime and accidents are counted the same as socially productive investments in healthcare, housing or transportation (Talberth *et al.*, 2007). Pollution can be seen as a double benefit to the economy because GDP increases both through the production of toxic chemicals and through cleaning up operations. For instance, exploitation of fossil fuels and forestry would result in higher GDP without considering environmental degradation and the reduction in the real welfare of society in the longer term (Perdan and Azapagic, 2011). These and similar irregularities within GDP indicate that social and environmental aspects can hardly be represented by GDP. Thus, recently a variety of alternative economic indicators have been developed that attempt to integrate conventional economic measures such as GDP with social and environmental costs and benefits that usually lie outside the accounting framework. The most common are the Measure of Economic Welfare (MEW), Index of Sustainable Economic Welfare (ISEW) and Genuine Progress

Indicator (GPI) (Ness et al., 2007). These economic indicators take into account non-market social benefits and cost deductions associated with degradation and depletion of natural resources.

Various measures of social progress such as poverty, inequality and quality of living have been used in assessing social progress, however formal research into social indicators did not start until the middle 1960s. By the late 1980s, various organisations and international agencies were formed that attempted to establish social measures of progress (Macgillivray and Zadek, 1995). A number of social indicators have been developed that address gender, health, housing and other social issues. In 1990 the United Nations developed the Human Development Index (HDI), which has gained some credibility and acceptance, and is, perhaps, the closest social equivalent to GDP (Patterson, 2006). Social indicators are usually the most difficult ones to measure and assess quantitatively. They are often of qualitative nature and could be highly subjective (Jeswani *et al*., 2010).

Prototype environmental indicators and indices started to emerge in the 1970s in North America and Europe. In 1991 the OECD and the Canadian Government both revealed preliminary work on environmental indicator sets. The emphasis of this work was mostly on the human pressures on the environment, such as pollutants and atmospheric emissions. After the Earth Summit in 1992, a large number of international, national, local, corporate and industrial environmental indicators were developed and incorporated into sustainability assessment and reporting (Macgillivray and Zadek, 1995). Identifying an appropriate set of indicators and indices (composite indicators) has become an initial part of any sustainability evaluation process and subsequent reporting of the sustainability performance (Singh et al., 2012).

The concept of sustainable development implies that the three aspects of sustainability – economic, environmental and social have equal values and should be integrated in a rational and coordinated manner (Pastille, 2002a). Thus, when talking about measuring sustainability, it is important to carefully choose the set of three types of indicators to evaluate the progress of reaching the specific goals and targets in all areas. Therefore, a development of ‘sustainability indicators’ has become an essential element of the recent international and national policies and strategies (Reed et al., 2006).

2.2. Characteristics, functions and criteria of the sustainability indicators.

Sustainability Indicators (SIs) represent elements or processes of real world systems and have specific (typically numerical) values that have a special meaning. The numerical value is a key feature of the SIs. “Indicators arise from values (we measure what we care about), and they create values (we care what we measure)” (Meadows, 1998). Other main features of SIs are their capacity to summarise, focus and compress the vast complexity of our dynamic environment to a manageable quantity of important information (Singh et al., 2012; Warhurst, 2002). Numerical SIs can be calculated in many different ways such as per time period, or per area, per total population, per capita, etc. and allow one to assess the progress of a project, process, region, city or country towards a specific goal. The values of the indicators can have different forms:

- Nominal scale: consists of two binary values yes or no. It can be meaningless in terms of quantitative information, however in controversial cases it is often used to agree on a solution.
- Ordinal scale: based on a hierarchy of qualitative states, such as the quality of training provided for the employees. The hierarchy has to be unambiguous with different defined classes for these scales to work correctly.
- Cardinal scale: provides quantitative information. In sustainability goals are linked to targets, hence the progress can be measured. Quantified targets have to be agreed on before deriving the scale (Mulder, 2006).

By simplifying complex phenomena, SIs may help politicians, industry leaders and other stakeholders to define specific targets, linking them to understandable objectives and real life projects. Scipioni et al. (2008) argue that the core function of the indicator is to represent the analysed problems in a way that maintains the informative content of the evaluation. Donnelly et al. (2007) argue that the main function of a sustainability indicator is to reduce the volume and complexity of information which is required by decision makers. For example, water or air quality indices are the most common environmental quality indicators. However, these indices are calculated using a lot of data based on the concentration of chemicals and pollutants in water and air. Decision makers and other stakeholders do not have to know all the details behind these calculations; it is the purpose of the indicator to communicate this complex information in an accurate and understandable way to influence a decision making process (Donnelly *et al.*, 2007).

The main purposes of sustainability indicators are summarised in figure 2.1.

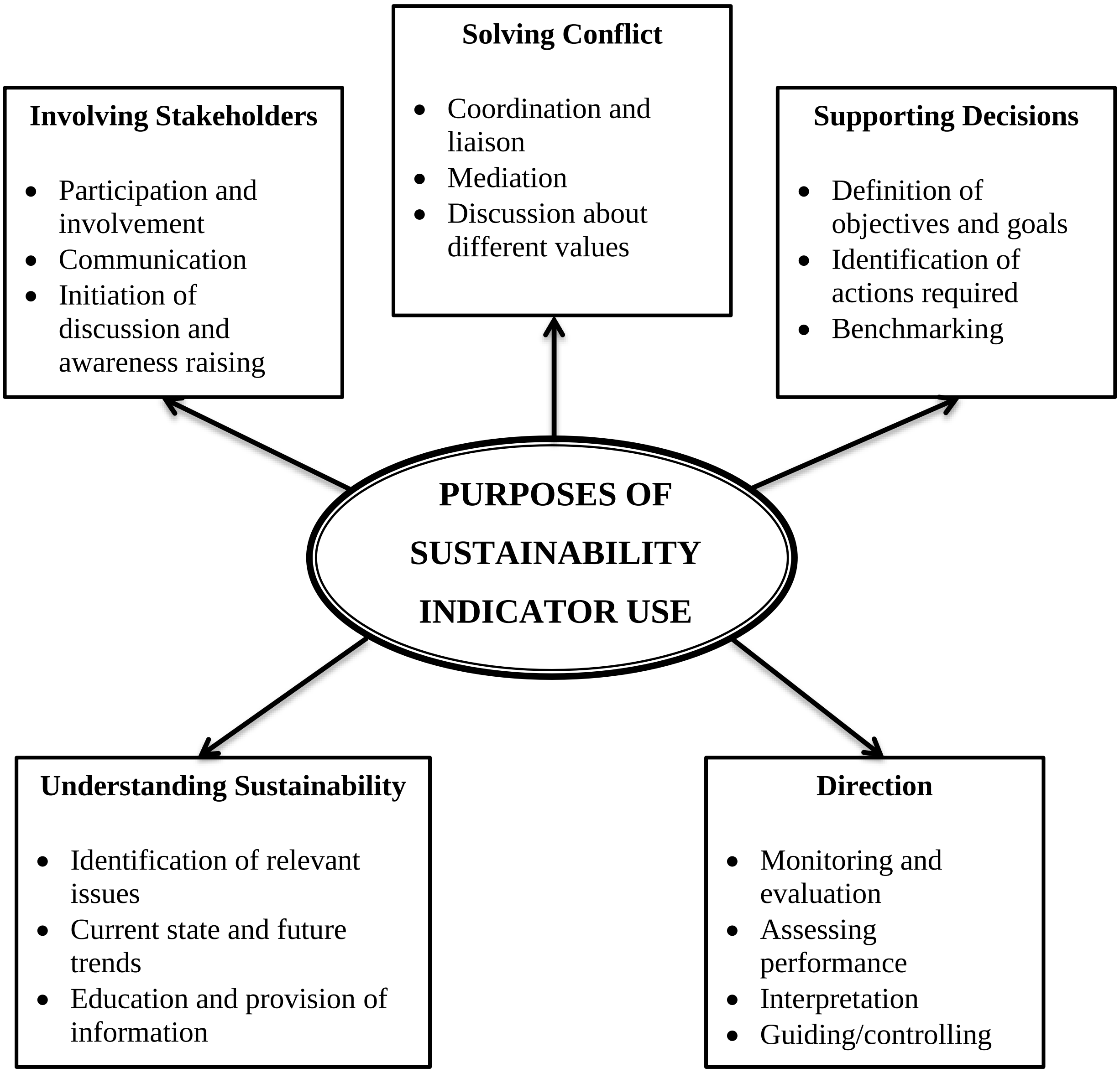


Figure 2.1. The main roles of sustainability indicators. Adapted from Pastille, 2002b.

Sustainability indicators must satisfy a certain number of criteria. The summary of main criteria is provided in figure 2.2.

CRITERIA FOR SUSTAINABILITY INDICATORS

MEASURABLE

- Be easily measured;
- Use existing and available data;
- Be reliable and consistent over time and space;
- Be scientifically robust and credible;
- Be verifiable and replicable;
- Have a target level, baseline or threshold against which to measure them;
- Be cost effective to measure.

CLEAR

- Be accurate and bias free;
- Unambiguous, easy to understand and interpret;
- Transparent and accountable;
- Be simple- the number of indicators should be limited and the way of calculating them transparent;
- Can detect changes at the appropriate temporal and spatial scale;
- Be easily accessible to decision-makers;
- Be based on well-understood and generally accepted conceptual models of the system to which they are applied.

RELEVANT

- Measure what is important for stakeholders;
- Be linked to practical action;
- Be policy relevant for all stakeholders, including the least powerful;
- Be directionally clear – they have to specify objectives and trends noticeably relevant in terms of significance for sustainability, therefore be able to indicate the progress or the lack of it;
- Predict changes that can be averted by management actions.

Figure 2.2. Criteria of sustainability indicators (Reed et al., 2006, Ugwu et al., 2006, Valentin and Spangenberg, 2000, Meadows, 1998, UNCCD, 1994, Braat, 1991, Zhen and Routray, 2003, Dale and Beyleler, 2001, Pastille, 2002a).

Not all indicators, however, can satisfy all the above criteria. In some cases, the accurate data cannot be obtained, thus some assumptions have to be made. In other cases, particularly in regards to the social aspects, the indicators cannot be measured in quantifying terms. In many circumstances, aggregated indicators can be unclear, ambiguous and difficult to interpret due to a large number of data hidden behind the final value. Identifying a core set of sustainability indicators for the evaluation of a specific project or process is a prerequisite for any sustainability assessment. However there are a number of pitfalls in SIs development and use. The most common of these are the following:

- The indicators cannot explain all the complexities of the ecosystems and economic systems; thus, often they cannot provide the exact answer and could only be used as a guideline.
- Not presenting sufficient numbers of indicators for each component in the framework may lead to misleading interpretation. Indicators that are only presented as percentage deviations from a baseline or, the ones that use a comparison without presenting the absolute values may not give the whole story.
- The existing data is often used instead of collecting new data, which leads to measuring what is easier and not what is important to measure.
- Aggregated indicators (indices) can lead to a misrepresentation of the correlations between the component parts.
- The indicators could be easily intentionally misrepresented to support a predetermined particular result rather than letting the indicator illustrate a neutral story (Olewiler, 2006).

2.3 Classification of the sustainability indicators.

2.3.1 Environmental, economic and social indicators and indices.

All sustainability indicators are generally categorised into the main three areas: economic, environmental, and social. Economic indicators measure the costs, profits, expenditure, losses, etc. of a product, process or project. It can be an indicator, such as a cost of 1 litre of fuel and expressed in monetary terms; or an index (composite indicator), such as the Consumer Price Index (CPI) measured in more complex way and expressed as a weighted score of as a percentage of price change (ONS, 2013).

Indicators are often used at a process and project levels, while indices are used at a state level.

Social indicators measure the state of human welfare, quality of life, equity, justice, etc. Social indicators can be highly subjective because of the different perceptions of different stakeholder groups. Various types of social indicators are used at project or national levels. At a project level, indicators such as Gender equality (e.g., % of women in employment or % of women in management positions) are typically used. At a national level, composite indices such as Well-being Index (WBI) (see section 2.6.3) are normally used that allow comparison of the overall social welfare levels of different states.

Environmental indicators are those that measure the state of the ecosystem and environment. They can also be classified into indicators and indices. The example of an indicator is the amount of GHG emissions resulting from the combustion of 1 tonne of coal. The example of an index is the Environmental Sustainability Index (ESI) which is comprised of a set of 21 indicator groups and 76 variables (Siche et al., 2008).

A set of indicators varies significantly depending on the type and scope of the project. Table 2.1 provides an example of some sustainability indicators used in a typical infrastructure project.

Table 2. 1. Sustainability indicators for the assessment of a typical infrastructure project.

Economic	Environmental	Social
- Total job creation (number of jobs) - Annual operating costs of venues(£) - Expenditure on the personnel training (£/per employee) - Cost of area regeneration (£/m^2)	- GHG emissions (tCO_2/MWh) - Water demand (litre per person per day) -Water reuse (greywater) (% of building water consumption) - Waste generation (tonnes per day)	- Gender equality (% of women in employment) - Number of injuries during the construction of infrastructure - On-site employees' facilities on-site - On-site employees' health and safety

- Construction costs (£/m^2) - Average cost of 1 kWh of diesel (£/kWh) - Revenues from sales (£)	- Energy consumption (electricity and gas) (kWh/day) - Renewable energy consumption (% of the total energy use) - Air quality (particulates and SO_x (kg/MWh))	- Proximity of medical facilities - Accessibility to public transport - New workspace created (m^2 per 100 dwellings in the local borough) - % of employees from the local areas

Frequently, SIs are referred to as environmental indicators, however sustainability indicators are different from classical environmental indicators as they do not only reveal the environmental status, but also specify interactive features between socio-economic and ecological systems (Opschoor and Reijnders, 1991). Environmental indicators are used to provide the environmental data in a comprehensive manner. Their purposes are:

- Environmental performance reporting;
- Derivation and pursuit of environmental targets;
- Comparison of environmental performance over time and between firms (benchmarking);
- Highlighting of optimisation potentials;
- Identification of market chances and cost reduction potentials;
- Technical support for the European Eco-Management and Audit Scheme (EU-EMAS) Regulations and ISO 14001 (Jasch, 2000).

It is argued that due to the multifunctional nature of environmental indicators their development and selection has become a fairly complex process (Kurts *et al*., 2001). They have to reflect a large number of environmental issues, forecast change, recognize stressors or stressed systems and influence management decisions (Donnelly *et al*., 2007). A number of frameworks based primarily on the environmental indicators have been developed and widely incorporated into practice.

The Pressure-State-Response (PRS) framework described in the section 2.3.2 provides an example of such framework.

2.3.2 Pressure-State-Response environmental indicator framework.

The Pressure-State-Response indicators are the components of the PRS framework developed by the Organisation of Economic Cooperation and Development (OECD). Human activities, such as the use of natural resources, atmospheric emissions, land use and many others impose pressure on the environment. These environmental pressures are expressed by the pressure indicators in the PSR framework. State indicators illustrate the current situation of the environment. The Response shows the measures that are being taken to minimise the negative environmental impacts of human activities.

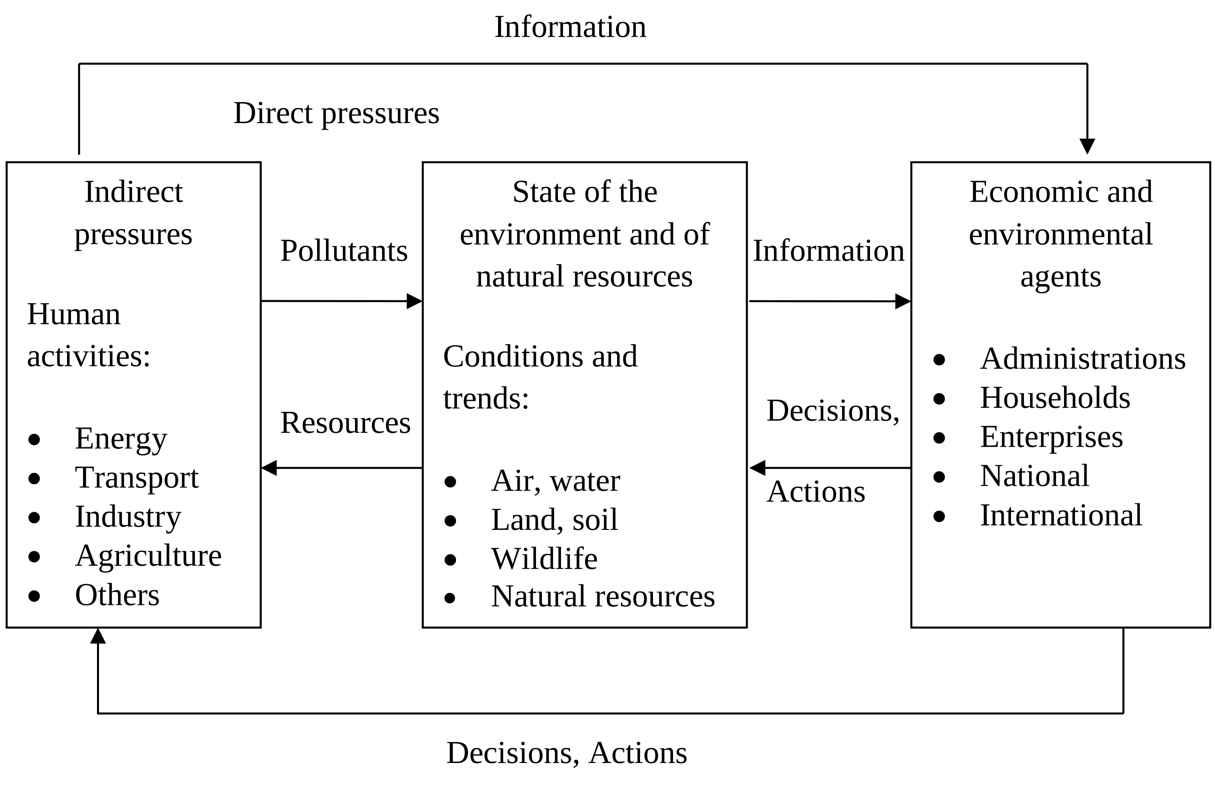


Figure 2.3. The Pressure-State-Response (PSR) framework. Adapted from OECD, 1998.

There is no general set of indicators for the PSR framework, the sets of SIs are chosen according to the needs of various stakeholders. A core set of approximately 40 indicators has been developed including the ones on the air quality, waste generation, water management, biodiversity, forest resources and land degradation.

Depending on the specific industry the additional sets of indicators are included to help the integration of environmental issues into the policy-making progress.

The PSR framework may be useful for assessing environmental issues, but it is not very practical when evaluating the economic and social aspects of SD. The assignment of the indicators to a specific category can be confusing as the same indicator can be allocated to two different categories, e.g. a response indicator can be at the same time a pressure indicator. For example, the pressure on the environment was caused by the application of pesticides which resulted in higher levels of chemicals in groundwater compared to the water quality standards. The response indicator was to increase taxes on the application of pesticides. However, another environmental pressure occurred because of it – the increased number of specific insects which affected the agricultural crops. Despite of the potential difficulties with allocation of certain indicators to a specific category, the PSR framework has been accepted by many authorities and a number of various other frameworks were developed based on the PSR model (Lundin, 2003).

One of the modified versions of the PSR frameworks has been created by the European Environmental Agency (EEA) and the European Statistical Office (Eurostat, 1997). This framework includes 2 more categories: Driving Forces and Impacts. Driving Forces include economic development, population, life style and education; Impacts include health–related features and biological effects. It was argued that the adjustments have made the PSR framework more complex, however at the same time also more flexible (Lundin, 2003). The Driving Force-Pressure-State-Impact-Response (DPSIR) framework is illustrated in figure 2.4.

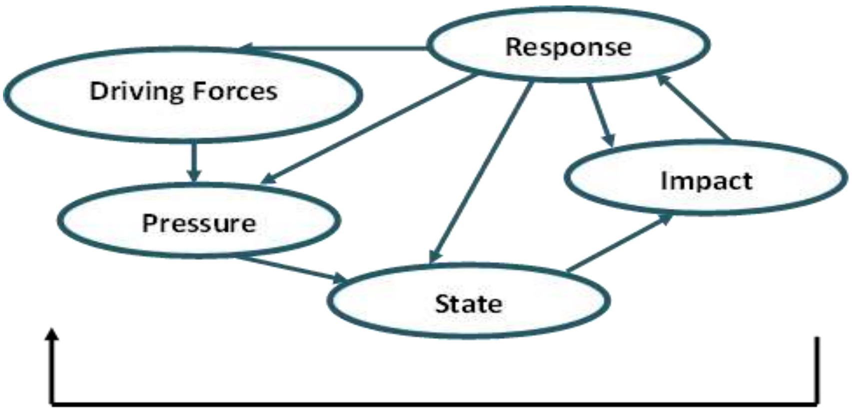


Figure 2.4. The Driving Force-Pressure-State-Impact-Response (DPSIR) framework. Adapted from Eurostat, 1997.

Most of the environmental indicators could be categorised into different types according to the DPSIR framework. The indicator types and examples are provided in table 2.2. In this work, the DPSIR framework was used to identify the main state, target and pressure indicators relevant to the objectives of the proposed methodology.

Table 2.2. Different indicator types. Adapted from Pastille, 2002b.

Indicator Type	Description	Example
State indicators	Specify the state of a system at a specific point in time (similar to impact indicators)	Current ambient air quality; noise levels near main roads; sea level rise; concentration of lead in urban areas
Target or goal indicators	Specify an envisaged state of a system in the future	Standard for desired air quality; benchmark for noise levels
Pressure indicators	Specify those variables which directly affect the environment	Toxic emissions; GHG emissions; noise; amount of waste generated
Driving force indicators	Refer to socio-economic or socio-cultural factors that increase or mitigate pressure on the environment	Development of industry, agriculture; population growth; prosperity levels; GDP, energy generation; mining
Rate indicators	Specify the velocity of change of the state of a system	Decrease of ambient air quality within a year; sea level rise per decade
Impact indicators	Specify the ultimate effects of changes of state, factors which give rise to a change of system (very similar to state indicators)	Percentage of children suffering from lead-induced health problems; decrease in agricultural production; hurricanes; floods; changes in species abundance
Response indicators	Specify the efforts of society (politicians, decision-makers, technical professionals) to solve the problem	Air quality improvement programmes; percentage of cars with catalytic converters; pollution levy revenue; taxes; price of petrol/diesel; maximum allowed noise levels

Steering indicators	Specify measures which indirectly aim to influence the process of change towards a desired situation	Development of public transport infrastructure; development of new sustainable energy sources
Process indicators	Specify measures which relate directly to aspects of the process by which change will be achieved (appraisal and output indicators)	Change in car mileage driven in a given period in a town centre; number of jobs created from a project

The Pressure-State-Response framework is being widely used by many government and business organisations. However, it has a number of weaknesses. It is argued that this framework attempts to get hold of causal links within a system but fails in terms of identifying comprehensive information to support decision making. In particular, it falls short in capturing information on the behaviour and structure of the system in which the decisions are being made. Besides, some groups of the indicators, for example, the response indicators, are based purely on intuitive models that are not suitable for dealing with complex systems (Kelly, 1998).

Failing to capture the complexity of the system leads to failing to account for nonlinearities. Forrester (1992) and Kelly (1998) point out two fundamental sources of nonlinearities that are necessary for the appropriate illustration of corporate and economic behaviour. The first source is when the influence of an input to a policy is not merely proportional to the input. The second one is when policies or decisions are affected or limited by the interaction of two or more input variables. Thus, it is argued that a systems approach is needed to identify decisive information, which incorporates frameworks with other evaluation and modelling tools, for example system dynamics modelling (Kelly, 1998).

Sustainability assessment of complex systems led to the development of large numbers of sustainability indicators. Social, economic and environmental indicators can be categorised further into various groups and sub-groups. Sections 2.3.3 and 2.3.4 provide a summary of different categories of indicators.

2.3.3. Quantitative versus qualitative; objective versus subjective indicators.

Ideally, an indicator should have a specific numeric value that can be measured and used in benchmarking and target setting. An indicator that can be expressed in numbers is a quantitative indicator. Some indicators, however, are difficult to measure numerically; therefore, they are expressed using words, colours or symbols. These are qualitative indicators. Many social indicators are often qualitative.

An objective indicator specifies facts that can be measured by various people to give the same results. A subjective indicator is based on opinions and perceptions. Subjective indicators are normally used when issues are too complex or impossible to measure in quantitative terms (e.g. degree of satisfaction with a service) (Pastille, 2002b). Table 2.3 provides some example of these types of indicators.

Table 2.3. Quantitative vs qualitative, subjective vs objective indicators. Adapted from Pastille, 2002b.

Type of indicator	Example
Quantitative objective indicator	Amount of CO_2 emission (in tonnes per tonne of product produced)
Quantitative subjective indicator	A specific numeric score given by the local resident to a survey of air quality in the area
Qualitative objective indicator	The colour of polluted water
Qualitative subjective indicator	A descriptive answer of a local resident to a survey of how safe he/she feels in the area after dark

2.3.4 Retrospective versus predictive indicators.

Braat (1991) distinguishes between the two types of sustainability indicators according to the information they provide on a temporal scale: predictive and retrospective. The predictive indicators deliver direct information about the future state and development of relevant socioeconomic and environmental variables. This information is used for planning and management and is based on mathematical models of the human-environment systems. The retrospective indicators provide information about the efficiency of existing policies and consist of the conventional policy appraisal and historical trend indicators.

Retrospective indicators are quantified by a collection of measured data and reference values, such as historical conditions, economic targets, environmental and health standards. Using only retrospective indicators, however, is not enough for successful policy-making as they can only point out to the past events. Thus, predictive indicators are necessary in order to forecast the future behaviour of the system. Despite the fact that predictive indicators are scientifically arguable and risky in practical administration it is argued that the consideration of both types of indicators is crucial in decision-making process (Braat, 1991).

Measuring and reporting sustainability has to be clear so that the progress can be tracked over time. A growing number of various categories of sustainability indicators led to the development of various frameworks, in which all indicators are divided into a number of main themes and sub-themes. The next section provides an overview of the main sustainability theme indicator frameworks.

2.4 Theme indicator frameworks.

2.4.1 The UNCSD Theme Indicator Framework.

Many sustainability indicator frameworks started to evolve after the Rio Earth Summit in 1992 and publishing the Agenda 21 in 1993, which states that "indicators of sustainable development need to be developed to provide a solid base for decision-making at all levels and to contribute to a self-regulating sustainability of integrated environment and development systems" (Agenda 21, 1993). After numerous discussions at the international forums and conferences in 1995, the United Nations Commission on Sustainable Development (UNCSD) indicator framework was developed. This, and subsequent indicator frameworks described in this section, are normally called 'theme indicator frameworks' because all indicators are distributed according to different themes, e.g. economic indicators.

The UNCSD framework has initially developed a list of 134 sustainability indicators, divided into 4 main categories. This framework includes institutional groups in addition to the 3 well-known economic, environmental and social groups. These groups are divided into 15 sub-groups, which are split further into 38 themes. This framework was developed to assist in sustainability assessment of various states and includes indicators such as per capita GDP, investment share in GDP, annual consumption of energy per capita, consumption of renewable energy, foreign direct investment, population growth rate, net migration rate, life expectancy at birth, unemployment rate, population density, forest area change, waste water treatment, land use changes and others (Eurostat, 1997).

Not all of SIs used in this framework could be applicable to local-level or industry/business-level assessment. However, some core indicators such as greenhouse gas (GHG) emissions, energy consumption, renewable energy use, etc. are being incorporated into many other sustainability frameworks. The UNCSD framework is illustrated in figure 2.5.

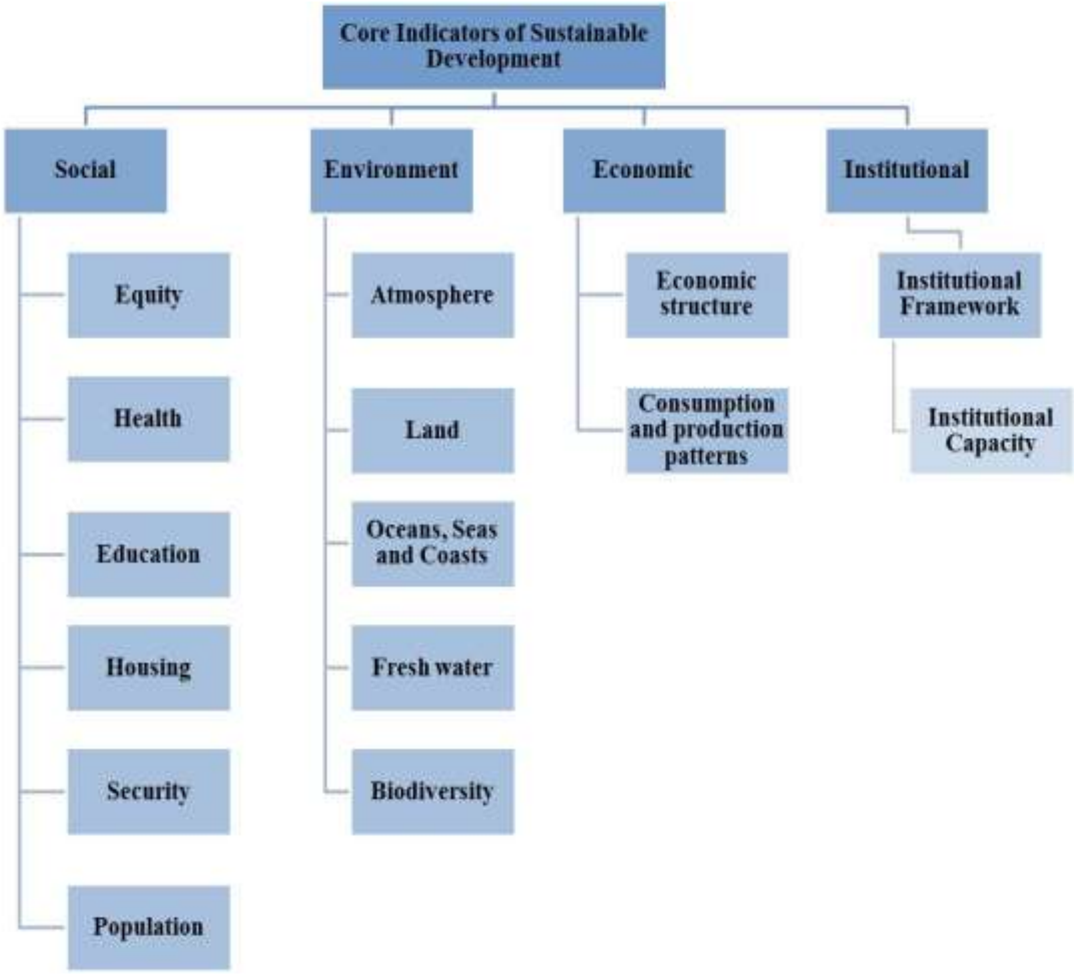


Figure 2. 5. The UNCSD Theme Indicator Framework. Adapted from Singh et al., 2012.

2.4.2. The Institution of Chemical Engineers (IChemE) Sustainability Metrics framework.

A company's aim of sustainability evaluation is to direct their product, process and personnel development and to safeguard their position in the fast changing circumstances of environmental legislation and stakeholders concerns. The set of indicators published by the Institution of Chemical Engineers (IChemE) can be used to evaluate sustainability performance of different operating units (a process plant, a group of plants, supply chain, etc). The information can be collected from a number of operations and aggregated to see the performance of a larger operation, a company, an industry as a whole or of a certain region (IChemE, 2002). The IChemE Sustainability Metrics framework is provided in figure 2.6.

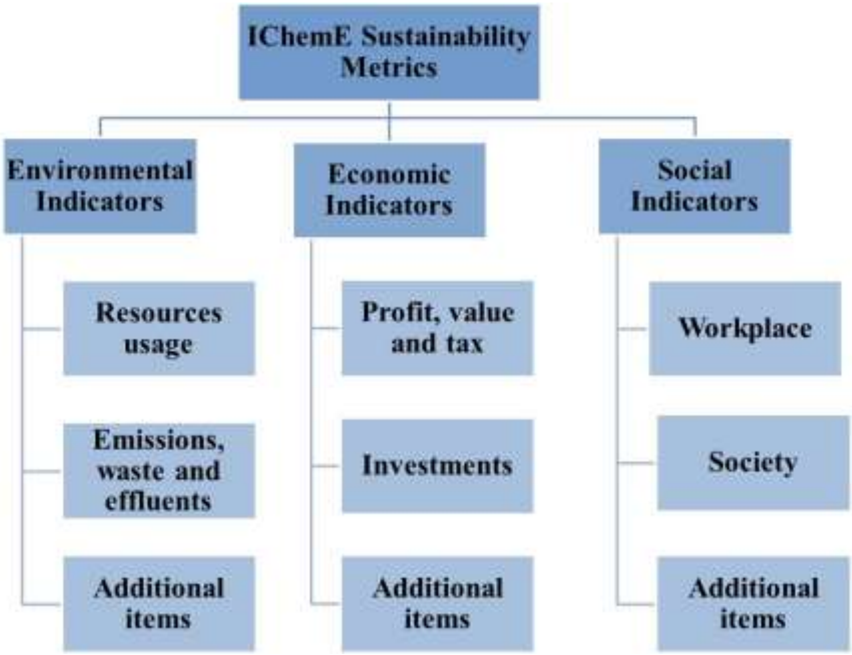


Figure 2. 6. IChemE Sustainability Metrics. Adapted from IChemE, 2002.

The IChemE Sustainable Development Progress Metrics is an impact orientated framework specifically recommended to measure the sustainability of operations within the process industry. A number of key indicators are normally present in every sustainability report. However, not all the metrics are applicable to any operational unit. The respondents can include other indicators of their choice in each category. For example, additional environmental indicators can be: compliance with regulations, environmental impacts of plant construction and decommissioning, or impact on biodiversity (IChemE, 2002).

The IChemE framework is less complex than the UNCSD one; however it strongly favours environmental aspects and quantifiable indicators that may be impractical in some operational practices, for example in the early phases of a project's life cycle (Labuschagne *et al*., 2005).

The IChemE framework is widely used in the process industry. The key performance indicators are divided into three categories – economic, environmental and social. The indicators are quantitative, thus the progress towards the specific goals is constantly monitored to identify the areas that require improvement.

2.4.3. The Global Reporting Initiative (GRI) framework.

In 1997, the United Nations Environmental Programme (UNEP) together with the United States non-governmental organisation, Coalition for Environmentally Responsible Economics (CERES), launched the Global Reporting Initiative (GRI) with the aim of 'enhancing the quality, rigour and utility of sustainability reporting (GRI, 2011). Reporting is, therefore, the strong emphasis of the guidelines. The GRI uses a hierarchical framework in three focus areas – social, environmental and economic. The hierarchy is comprised of different categories, indicators and metrics. The guidelines address more than 100 indicators. The guidelines indicate what should be considered at a lower level such as operational or project level within the company, especially if the company reports on sustainability using the GRI principles (Labuschagne et al., 2005). However, not all of the indicators are easy to evaluate and no guidance is provided on how to choose an appropriate indicator (Veleva and Ellenbecker, 2000).

The hierarchical structure of the GRI framework is provided in figure 2.7.

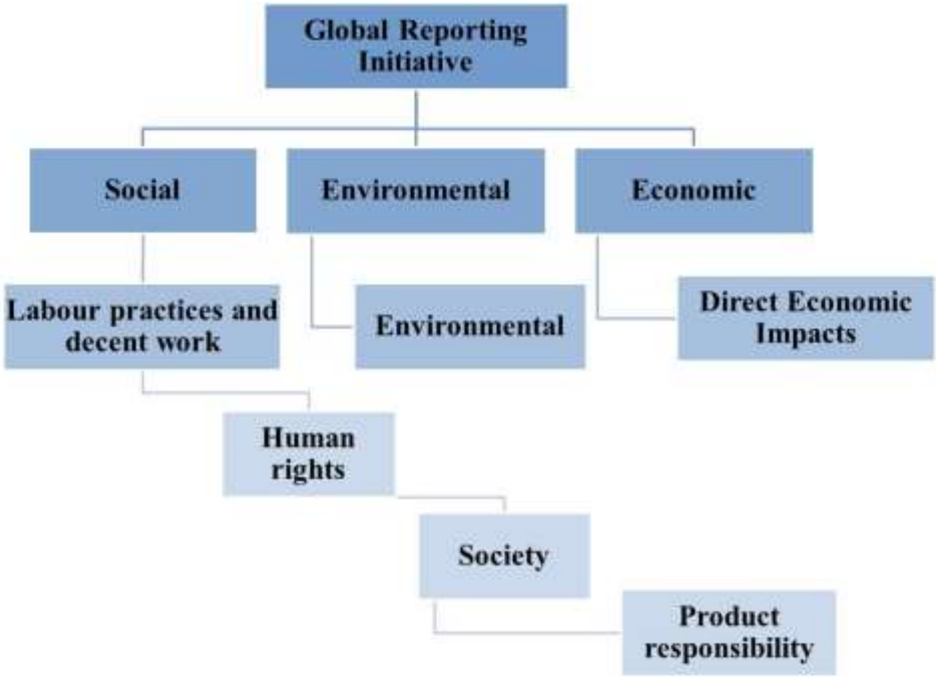


Figure 2.7. The hierarchical structure of the global reporting initiative (GRI) framework. Adapted from GRI, 2011.

2.5. Categories of sustainability assessment tools.

The frameworks described in section 2.4 were developed to facilitate the reporting of sustainability performance in a structured way according to the specific indicator groups applicable for a particular project or process. Sustainability frameworks, however, do not provide any guidance on how to measure the indicators or which assessment techniques and methods should be used.

Sustainability is not a fixed goal; it is an on-going process (Porritt, 2007). In order to determine how sustainable the process or project is, its performance should be monitored and recorded on a regular basis. This allows tracking and reporting the progress towards a specific target, comparing different indicators' values over a certain time period and optimising the overall process or operation. This section provides the summary of the main sustainability assessment tools currently used in practice to measure performance of different aspects.

Gasparatos (2010) explains the distinction between frameworks (such as those discussed in section 2.4) and evaluation tools, which are described in sections 2.6-2.10. He defines frameworks as integrated and controlled procedures similar to protocols, which allow the comparison of various options based on their total sustainability impact. Frameworks consist of a number of indicator categories. These categories have to be assessed in order to achieve an overall goal. However, frameworks do not specify the analytical tools that have to be used for the investigation of different project options.

The assessment tools are different analytical techniques that can be used to carry out analysis within the frameworks. These tools strive to understand a system and present the information in a way that can assist the decision making process (Gasparatos et al., 2009). This is normally done by quantifying certain relevant criteria (e.g. resource consumption, energy use, financial costs/benefits, etc.) and often aggregating these aspects (Gasparatos, 2010). The most commonly used evaluation tools include economic tools (e.g. Cost-Benefit Analysis, Life Cycle Costing) (Yang et al., 2013; Singh et al.; 2012, Azapagic, 2011), biophysical models (e.g. Energy Flow Analysis, Material Flow Analysis) (Ness et al., 2007; Utlu and Hepbasli, 2007), indicator lists/composite indices and Multi-Criteria Decision Analysis (MCDA) (Wang et al., 2009; Jeswani et al., 2010). Sometimes these tools are named environmental evaluation tools, but it is argued that all of them can be used to assess social and economic aspects and, therefore, should be referred to as sustainability evaluation tools (Gasparatos et al., 2009, Ness et al., 2007).

A wide range of quantitative and qualitative tools for sustainability assessment (SA) have been developed by scientists and different industries in the last few decades. Some tools and frameworks were developed by international or national governmental bodies; they provide guidelines on sustainability assessment on regional or country levels. Other tools were developed for specific industries, businesses and engineering processes. They are more explicit with defined sets of indicators that are developed particularly for the sustainability assessment of this certain project or process.

Ness et al. (2007) categorised sustainability assessment tools according to the scheme illustrated in figure 2.8. Only a selected number of present sustainability assessment techniques that have been mentioned more frequently in the literature are presented in this scheme. There are, however, many other tools that are being used and developed taking into account the changing nature of business processes, technological developments and implementation of new policies and legislations.

The tools are divided into the following three categories:

1. Indicators and indices. This category is divided into three sub-categories: non-integrated, integrated and regional flow indicators;
2. Product related assessment. This category includes such tools as Life Cycle Assessment, Life Cycle Costing, Product material flow analysis and Product energy analysis;
3. Integrated Assessment. This category comprises Conceptual Modelling and System Dynamics, Multi-Criteria Decision Analysis, Risk and Uncertainty analysis and various types of Impact Assessment.

This scheme also indicates the time factor of the tools – whether they look back in time (retrospective) or if they are looking forward (forecasting, prospective). The monetary valuation tools are provided on the bottom of figure 2.8. They are used when monetary estimation is needed. The boxes with bold lines around them show those tools that can integrate nature-society systems into a single evaluation.

This scheme is a summary of the major tools used in sustainability evaluation of various projects and processes. It can be used in order to determine a set of SA tools for a particular project or process. For example, one project may require more thorough evaluation of its environmental impacts, while others may need more risk and uncertainty assessment. Sometimes more than one tool can be chosen to measure the same aspect to validate the results, however it can be time consuming and less cost effective.

The assessment tools can be divided into the two main categories: reductionist and non-reductionist. Economic tools, biophysical models and composite indices are reductionist tools; MCDA and indicator frameworks are non-reductionist (Gasparatos, 2010). Munda (2006) characterises reductionist tools as those ones that use a single measurable indicator (e.g. economic profit), a single dimension (social, environmental or economic), a single scale of analysis, a single objective (e.g. minimisation of waste generated) and a single time horizon. Another typical feature of the reductionist tools is the tendency for quantifying and aggregating various sustainability aspects with a single measurement unit. These tools can simplify and incorporate diverse issues into a small set of numbers, which is invaluable for policy makers. However, sometimes the loss of important information may occur during the aggregation process and significant data can be concealed behind the final aggregated indices. Thus, non-reductionist tools such as MCDA are often used for decision-making purposes. In this case, a set of indicators and their values are presented for consideration which provides more details on specific indicators. It is important that no matter which sustainability tools are used, they must be accurate, robust and supported by strong scientific base and practical facts in order to avoid ambiguous policy messages (Gasparatos et al., 2009).

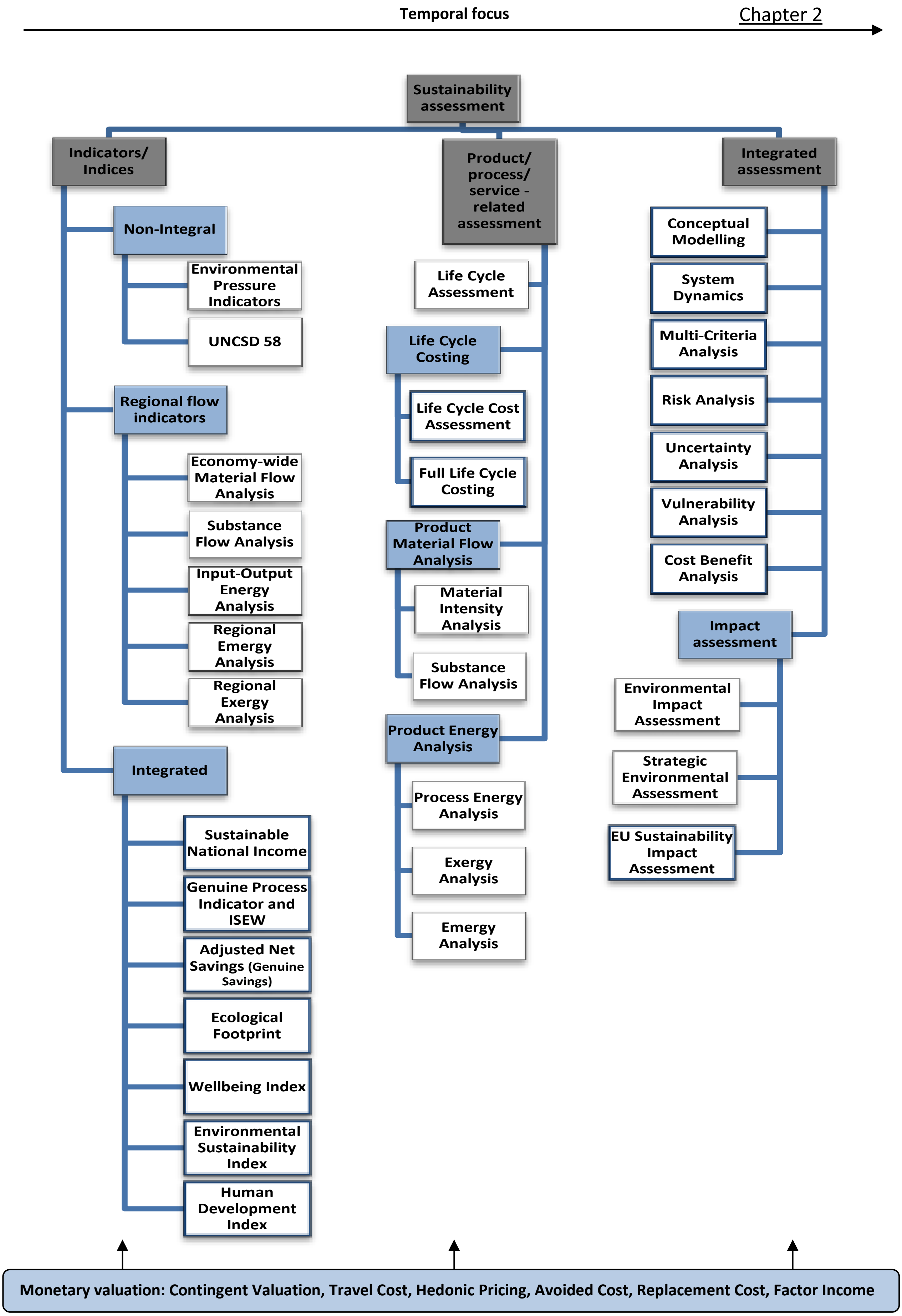


Figure 2. 8. Summary of sustainability assessment tools. Adapted from Ness et al., 2007.

2.6. Indices.

A number of sustainability indicators can be presented in a form of a theme framework, or they can be aggregated into an index (in some cases referred to as a composite indicator). Mayer (2008) describes an index as a 'quantitative aggregation of many indicators that can provide a simplified, coherent, multidimensional view of the system'. Selection of SIs for indices requires a balance between simplification and complexity. The indicators should be valid, reliable, comparable and concise and provide the necessary data (Singh et al., 2012).

Many indices have been developed in the last few decades to address various aspects of sustainability. It is argued, however, that many of these indices integrate the same data taken from the existing global sustainability databases. They also use the same methods of data aggregation. The most common aggregation methods are sums, averages, ratios, regression analysis, principal components and others (Mayer, 2008). Singh et al. (2012) categorise the sustainability indices into the following groups:

- Innovation, Knowledge and Technology Indices;
- Development Indices;
- Market- and Economy-based Indices;
- Eco-system-based Indices;
- Composite Sustainability Performance Indices for Industries;
- Investment, Rating and Asset Management Indices;
- Product-based Sustainability Indices;
- Sustainability Indices for Cities;
- Environmental Indices for Policies, Nations and Regions;
- Environment Indices for Industries;
- Energy-based Indices;
- Social and Quality of Life-based Indices.

There are many dozens of various sustainability indices currently used in practice. In this section, a short summary of three widely used indices is provided to demonstrate the use of aggregated indices and examine their benefits and pitfalls. Ecological Footprint Index is widely used in environmental assessment and is easily communicated to a wide range of stakeholders. Sustainable Process Index is generally used to evaluate the sustainability of industrial processes. Well-being index is based on socio-economic and environmental indicators and is broadly used for decision-making purposes.

2.6.1. Ecological Footprint Index (EP).

The Ecological Footprint (EF) (Wackernagel and Rees, 1997) ‘quantifies for any given population the mutually exclusive, biotically productive area that must be continuous to provide its resource supplies and to assimilate its wastes’. In other words, EP accounts the land, water and other resource supply chains and disposal management options necessary to sustain a national living standard into infinity. Land and sea are divided into five components: bio-productive land, bio-productive sea, energy land, built land and biodiversity land for non-human species. Footprints are calculated based on either compound or component or combination of these methods. The calculations of the EF are based on the national consumption statistics data. The ratio of required resources to available resources is calculated. If this ratio is more than one, then the living standards are considered to be unsustainable (Böhringer and Jochem, 2007).

There are some useful features of EF index. It takes into account resources consumption, population size and provides information on demand of the human societies on natural ecosystem support. It is a standardised, straightforward, flexible and visual tool that can effortlessly be communicated to the non-experts. However, it is also argued that the EF index is a weak sustainability tool that cannot take into account pollution and significant environmental impacts other than those that can be interpreted as a loss of bioproductive land. In addition it cannot quantify resource depletion that is not translated to a bioproductive area (e.g. minerals) (Gasparatos et al., 2008).

2.6.2. Sustainable Process Index (SPI).

Sustainable Process Index (SPI) is a greatly aggregated index that measures the whole environmental impact of different human activities (Krotscheck and Narodoslawsky, 1996). It was created to evaluate industrial processes and is based on mass and energy balances. Extraction of raw materials, energy use, physical installations, air emissions and waste generation are some of the human activities that impact the environment. The SPI has to consider different aspects of these impacts. The total area for sustainable introduction of a specific process into the ecosphere is given by:

$$A_{tot} = A_R + A_E + A_I + A_S + A_D, \qquad (2.1)$$

where A_R is the area for raw material extraction;
A_E - the area for energy provision;
A_I - the area attached to physical installations;
A_S - the area to support the staff;
A_D - the area necessary to disperse all wastes, emissions and products linked to the process in question of sustainability to the ecosphere.

Services and goods are the products of the processes; therefore the impact per good or service unit is important. It is characterised by

$$a_{tot} = A_{tot}/N_P, \qquad (2.2)$$

where N_P is the number of goods or services produced by the process.

Ultimately, it is possible to relate the specific area of a certain service or good to the area statistically available to a person to provide all services and goods in a sustainable way, which gives a SPI:

$$SPI = a_{tot}/\ a_{in}, \qquad (2.3)$$

where a_{in} is the area at disposal for each person in a given region (Narodoslawsky and Krotscheck, 2004).

Any stream leaving a process in the SPI approach is considered to be a product stream, whether it is a valuable product or a waste stream. It is also assumed that all products ultimately dispel into the environment and this forms the basis for calculating the area needed to accommodate products A_D. Thus, the SPI estimates the amount of area required to sustainably embed a process into the environment. This is a different environment tool from LCA (described in section 2.7.1.), which directly analyses the waste streams leaving a process and quantitatively assesses the environmental impacts of these streams (Steffens *et al*., 1999).

It is argued that the major attribute of the SPI assessment is that it makes possible comparing the various impacts of a given technology, therefore it can be used to identify the ecological defects of technologies and can be used to optimise processes in line with their ecological impacts (Narodoslawsky and Krotscheck, 2004).

2.6.3. Well-being Index (WBI).

The Well-being Index (WBI) is an average of the Human Well-being Index (HWI) (an average of 36 standardised, equally weighted socio-economic indicators) and the Ecosystem Well-being Index (EWI) (an average of 51 standardised, equally weighted environmental indicators). The indices HWI and EWI consist of five sub-indices. The HWI includes Health and Population, Welfare, Knowledge, Culture and Society, and Equity Index. The EWI incorporates indices for land, water, air, species, and resource deployment (Böhringer and Jochem, 2007).

There are some pitfalls in using WBI. For example, if a country poorly monitors the sustainability performance in some aspects, it can in fact appear more sustainable due to the lack of data on the unsustainable features. It is also argued that individually the HWI and EWI can provide guidance to policy-makers, yet the WBI is not so easy in this respect (Mayer, 2008).

Although a large number of indices have been developed and used, it is pointed out that some of them fail to meet crucial scientific requirements. For example, there are no general rules for normalisation of the input variables and their weighting procedures, therefore sensitivity analysis should be carried out (Böhringer and Jochem, 2007). It is stated that sensitivity analysis will help to identify methodological biases and increase the transparency of the index to the decision-makers. It will allow identifying the indicators that represent the best option for improvement and those ones that require particular action (Tran *et al*., 2007).

2.7. Product, process and service-related assessment tools.

2.7.1. Life Cycle Assessment.

Life Cycle Assessment (LCA) is one of the most developed and widely used environmental assessment tools. It has been used for almost 40 years to assess the environmental impacts of a product or service during its whole life cycle. It is an approach that evaluates real and potential pressure that a product (in this case goods or services) has on the environment during extraction of raw materials, production process, use and disposal of the product (ISO, 2006a,b). The application of life cycle approach and LCA are now increasingly being required by various EU legislations, such as the Directive on Integrated Pollution Prevention and Control (IPPC) and within the Integrated Product Policy (IPP) (Azapagic *et al*., 2006).

The official ISO-definition states that LCA is 'the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle' (ISO, 2006a). The resource consumption and emissions are recorded and evaluated at all stages of the product life – from the extraction of raw materials, through the production, transportation of raw materials and products, distribution and the final disposal of the product. The limits of the evaluated system can be set according to the purpose and the scope of the assessment. For example, in chemical engineering a "cradle-to-gate" approach can be sufficient when comparing two alternative processes to the same product; or a "gate-to-grave" approach can be used when comparing two various end-of-life technologies (Jiménez-González and Woodley, 2010). Figure 2.9 is the graphic representation of the main activities typically included in LCA studies.

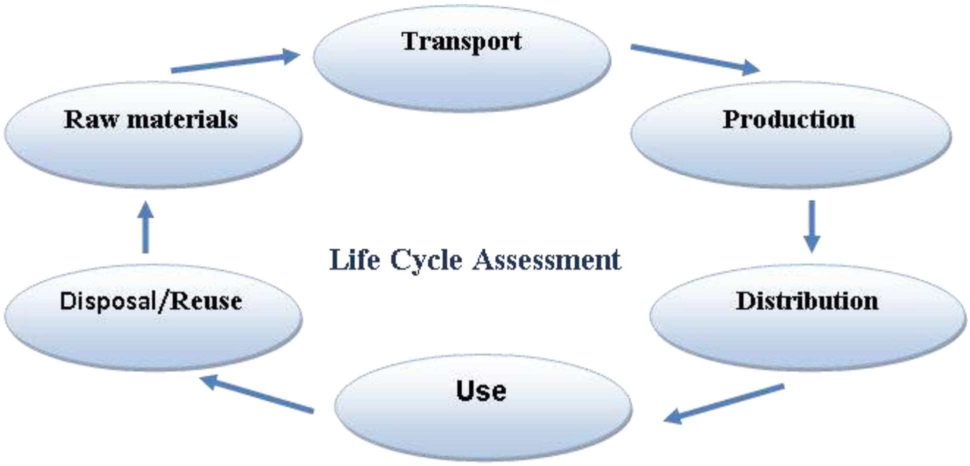


Figure 2.9. Life Cycle Assessment. Adapted from Jiménez-González and Woodley, 2010.

LCA allows the evaluation of the overall level of environmental sustainability, assists in identifying the main impacts for a particular process design, process optimization and process labelling. Moreover, it helps to determine the "hot spots" in the system, i.e. those parts that have the most significant environmental impact and should be improved first. Thus, it allows identifying more environmentally sustainable options (Azapagic *et al*., 2006).

The LCA methodology consists of four stages (ISO, 2006a):

1. Goal and scope definition.

The first stage includes a statement of the purpose of the study and its proposed use, description of the system and definition of the system boundaries, definition of the functional unit, identification of data quality requirements, the assumptions and limitations of the study. A functional unit is one of the most important components of an LCA study. It characterises a quantitative measure of the outputs delivered by the system. In comparative LCA studies it is essential to do the evaluations based on the equivalent functional units.

2. Inventory analysis.

The aim of this stage is to identify and quantify the environmental burdens in the life cycle of the activity. It includes detailed definition of the system, data collection and validation, allocation and estimation of environmental burdens. Environmental burdens for each subsystem are quantified according to the following formula:

$$B_j = \sum_{i=1}^{I} bc_{j,i} x_i \ , \qquad (2.4)$$

where $bc_{j,i}$ is burden j from subsystem or activity *i*,

x_i is a mass or energy flow associated with that activity.

3. Impact assessment.

At this stage the burdens are translated into the related potential environmental impacts (or category indicators). It involves selection of impact categories, category indicators and life cycle impact assessment (LCIA) models; classification (or aggregation) and characterization. Additional steps in this stage are: normalization, grouping and weighting of impacts.

4. Interpretation.

The last LCA stage includes identification of the main burdens and impacts, identification of 'hot spots', sensitivity analysis, evaluation of findings and further recommendations (Azapagic, 2011).

It is argued, however, that LCA is usually restricted to environmental aspects; therefore it is necessary to widen the scope of LCA adding economic and social dimensions. This does not mean that more numbers and more indicators will be produced during the extended assessment process; it means that results might be presented in the different form of eco-efficiency indicator, which comprises economic and environmental information in a combined manner (Heijungs et al., 2010).

2.7.2. Energy and exergy analysis.

Analysis of material and energy flows provides an outline of the structure of resource flows and identification of inefficiencies within a system. These studies could be used both to recreate historical flows and emissions and to forecast new ones for decision making process (Ness *et al.*, 2007). Unlike energy analysis that measures quantity of energy, exergy analysis measures quality of energy (Brunner and Rechberger, 2004).

Exergy is defined as the maximum theoretical work obtainable as the system is brought into equilibrium with its environment (Chen et al., 2014). Thus, exergy is the useful part of an energy flow that could be transformed into any other energy form. Exergy analysis allows comparison of all energy sources – renewable and not renewable, thus being a suitable extra parameter in evaluating the energy efficiency in buildings on regional or national scale and characterising both quantity and quality of various energy supply sources (Torío and Schmidt, 2010). Exergy analysis leads to a better understanding of the process effectiveness, environmental impacts and sustainability of the energy system, the influence of various thermodynamic factors and identification of the most effective ways of improving the process (Utlu and Hepbasli, 2007).

The mass balance can be expressed as:

$$\sum \dot{m}(in) = \sum \dot{m}(out)\,, \tag{2.5}$$

where $\dot{m}$ is the mass flow rate, inlet and outlet.
The general energy balance can be expressed as:

$$\sum \dot{E}(in) = \sum \dot{E}(out)\,, \tag{2.6}$$

where $\dot{E}(in)$ is the rate of net energy transfer in, $\dot{E}(out)$ is the rate of net energy transfer out by heat, work and mass.

The exergy balance can be expressed as:

$$\sum \dot{E}x(in) - \sum \dot{E}x(out) = \sum \dot{E}x(dest)\,, \tag{2.7}$$

where $\dot{E}x(in)$ and $\dot{E}x(out)$ are the rates of exergy transfer in and out, $\dot{E}x(dest)$ is the exergy destroyed.

The energy balance is the fundamental method of a process investigation. It allows energy analysis and points out the areas that need improvement. It is a key to optimisation and the base for developing the exergy balance. The exergy analysis is a thermodynamic method used as an advanced tool for engineering process assessment

(Szargut et al., 1998). The energy analysis is based on the first law of thermodynamics, while the exergy analysis is based on both first and second laws of thermodynamics. Energy and exergy analysis and optimisation of any physical or chemical process can offer two different views of the process (Utlu and Hepbasli, 2007).

Energy and exergy analysis is a flexible method that can be used at all levels: micro, meso and macro. Due to its flexibility it can be integrated with LCA, but there is a potential risk on concentrating too much on energy issues and leaving out other significant aspects (Jeswani et al., 2010).

This section provided an overview of those assessment tools that are typically used to evaluate the environmental and economic performance of a product, process or service in terms of materials and energy used and environmental burdens associated with it. The next section provides an overview of the integrated assessment tools which can be used for the integrated assessment of all sustainability aspects.

2.8. Integrated assessment tools.

2.8.1. Multi-criteria Decision Analysis (MCDA).

Multi-criteria decision analysis (MCDA) is a widely used decision making tool. It is a branch of the general class of operations research models that deals with the process of making decisions in the presence of multiple objectives (Begić and Afgan, 2007).

The first step in the MCDA is to formulate the set of selected criteria and to normalize the original data of criteria. The next step is to assign weights to the criteria. Then the alternatives are ranked by MCDA with criteria weights (Wang *et al*., 2009). An example of the MCDA decision matrix is illustrated in table 2.4.

The decision matrix is formed with design alternatives M and N criteria.

Table 2.4. MCDA decision matrix (adapted from Ugwu *et al.*, 2006).

	Sustainability criteria				
Design Alternative (Options)	**Sc_1 W_1**	**Sc_2 W_2**	**Sc_3 W_3**	**Sc… W…**	**Sc_N W_N**
D_1	$d_{1,1}$	$d_{1,2}$	$d_{1,3}$	$d_{1,\dots}$	$d_{1,N}$
D_2	$d_{2,1}$	$d_{2,2}$	$d_{2,3}$	$d_{2,\dots}$	$d_{2,N}$
$D_{\dots}$	$d_{\dots,1}$	$d_{\dots,2}$	$d_{\dots,3}$	$d_{3,\dots}$	$d_{\dots,\dots}$
D_M	$d_{M,1}$	$d_{M,2}$	$d_{M,3}$	$d_{\dots,\dots}$	$d_{M,N}$

MCDA is widely used in sustainability assessment, particularly in those cases where a single-criterion approach, such as cost-benefit analysis, is not applicable, particularly because some environmental and social impacts cannot be expressed in monetary or quantitative terms. MCDA can integrate all three aspects of sustainability and incorporate both quantitative and qualitative data, thus allowing decision-makers to include a full range of chosen criteria (Jeswani *et al.*, 2010).

There are a number of various MCDA methods. The weighted sum method (WSM) is often used in sustainability assessment of energy systems (Wang *et al.*, 2009). The score of an alternative is calculated as:

$$S_i = \sum_{j=1}^{N} d_{ij} W_j, \qquad i = 1, 2, 3, \dots, M \tag{2.8}$$

The scores for each alternative are calculated and the preferred design option will be the one with the highest score.

The weighted product method (WPM) is similar to WSM. The main difference is that the score of alternatives is calculated as the following multiplication:

$$S_i = \prod_{j=1}^{n} {d_{ij}}^{W_j}, \qquad i = 1, 2, 3, \dots, M \tag{2.9}$$

As in the WSM method, the alternative with the maximum score is the best option. Due to the exponent property, the WPM method requires all ratings be greater than 1. Alternative scores acquired by the WPM method do not have an upper numerical bound and in some cases it is difficult for a decision-maker to see the true meaning of the scores. Thus, it is often useful to compare each alternative with the standard score, with the ratio given by:

$$R_i = \frac{S_i}{S^*} = \frac{\prod_{j=1}^{n} d_{ij}^{\;W_j}}{\prod_{j=1}^{n} (d_j^{\;*})^{W_j}}, \qquad i = 1, 2, 3, ..., M \tag{2.10}$$

where d_j^* is the most favourable performance for criteria *j*. It is clear that the preference of alternative *i* increases when R_i approaches to 1 (Wang *et al*., 2009).

Another widely used MCDA method is the analytic hierarchy process (AHP) (Saaty, 1990). This descriptive method calculates ratio-scaled importance of alternatives by pair-wise comparison of evaluation criteria and alternative. The matrix of the AHP method is:

$$D = \begin{bmatrix} C_1 / C_1 & C_1 / C_2 & ... & C_1 / C_n \\ C_2 / C_1 & C_2 / C_2 & ... & C_2 / C_n \\ .... & .... & ... & .... \\ C_n / C_1 & C_n / C_2 & ... & C_n / C_n \end{bmatrix} \tag{2.11}$$

For each comparison the decision-makers have to state the strength of their preference for one alternative over another from equal importance to absolute preference (normally1 to 9 on the numerical scale) AHP is a type of weighted sum method. After obtaining the weights, each performance is multiplied with its weight. The overall weights with respect to goal for each decision alternative are then obtained. As in WSM and WPM methods, the alternative with the highest score is the best option (Wang *et al*., 2009). A downside of using pair-wise comparison methods such as AHP is the number of comparisons that the respondent group has to make. If there are too many comparisons to be made the respondent group tends to get tired and make comparisons of a lower quality as their will to discuss fades which generates poor results. Thus, the more alternatives in the assessment the more inappropriate the pair-wise comparison method becomes (Barfod *et al*., 2011).

Multi-criteria decision analysis has been widely used for decision-making purposes of sustainability assessment. It has a number of advantages over other evaluation methods because it can integrate qualitative and quantitative social, environmental and economic indicators, and thus can be more transparent and effective for the evaluation of complex sustainability issues. However, it can be time consuming, particularly when a large number of stakeholders are involved (Jeswani *et al*., 2010).

2.8.2. Cost-benefit analysis.

Cost-benefit analysis (CBA) is a widely used economic decision-making tool that evaluates a project in terms of total costs and potential benefits. CBA is also used when comparing alternative projects in order to estimate which one will be more profitable. In CBA all costs and benefits are expressed in monetary terms and then adjusted for the "time value of money", so that all costs are expressed in terms of their "present value". CBA is often used in sustainability assessment, particularly when evaluating environmental impacts of the proposed projects.

Any CBA consists of a number of stages. Hanley and Spash (1993) identify the following eight stages:

1. Definition of the project.

The purpose is to define the reallocation of resources and consider all potential stakeholders who might be affected by the project. Unless the project is defined clearly it cannot be assessed.

2. Identification of project impacts.

The aim is to identify all the impacts resulting from the implementation of the project.

3. Which impacts are economically relevant?

Assuming that society is interested in maximising the weighted sum of utilities across its members, at this stage it is necessary to identify the positive and negative impacts of the project as well as unpriced impacts (externalities).

4. Physical quantification of relevant impacts.

This stage entails determining the physical amounts of cost and benefit flows for a project and identifying the time when they will occur. All calculations made at this point will have different levels of uncertainty.

5. Monetary valuation of relevant effects.

All physical measures of impacts should be co-measureable; therefore, they have to be valued in common units. The general unit in CBA is money. The CBA analysts have to predict prices for value flows extending into the future, correct market prices where necessary, and calculate prices where none exist.

6. Discounting of cost and benefit flows.

Because the value of money in time changes, it is necessary to convert all money into present value (PV) terms. The PV is calculated as follows:

$$PV(X_t) = \frac{X_t}{(1+i)^t} \tag{2.12}$$

where t is time, i is the rate of interest or discount rate, X is a cost or a benefit.

Discounting in CBA can be done by two methods. The first one is to find the net value of benefits minus costs for each time period (normally a year) and discount each of these annual net benefits flows throughout the project's lifetime. The other way is to calculate the discounted values for each part of the project and then add up all the discounted elements.

7. Applying the Net Present Value test.

The main aim in CBA is to assist in the decision-making process on to whether the proposed project would be profitable or not. The Net Present Value (NPV) test is performed to find out if the sum of discounted benefits will exceed the sum of discounted losses:

$$NPV = \sum B_t(1+i)^{-t} - \sum C_t(1+i)^{-t} \tag{2.13}$$

where B_t is the benefit in time $_t$, C_t is the cost in time t, i is the discount rate.

If NPV of the project is less than 0, then the costs outweigh the benefits, therefore the project should not be implemented.

8. Sensitivity Analysis.

At this stage it is possible to determine which parameters of the NPV test most influence the outcome. Sensitivity Analysis is carried out by changing certain main parameters and recalculating NPV. These parameters often are:

- The discount rate;
- Physical quantities and qualities of inputs and outputs;
- Shadow prices of these inputs and outputs;
- Project life time (Hanley and Spash, 1993).

The application of CBA can be controversial because of the difficulties with monetising impacts, uncertainty about using money as the major value and discounting the future (Hacking and Guthrie, 2008). Different groups of people have different ideological orientations, thus their monetary values on certain issues might vary. Calculations in CBA are subjective because of the impact of wealth, income distribution, willingness to pay and scientific uncertainty and discount rates. Other shortfalls of CBA are distributional issues and reliance on experts (Bebbington *et al*., 2007).

2.8.3. Environmental Impact Assessment.

There are various definitions of Environmental Impact Assessment (EIA). The most recent definition adopted by the International Association for Impact Assessment (IAIA, 2009) is the 'process of identifying, predicing, evaluating and mitigating the biophysical, social and other relevant effects of the proposed development proposals prior to major decisions being taken and commitments made'. It is argued that EIA is a systematic process that examins the environmental consequences of the development actions (Glasson et al., 2012). The main difference between the strategic environmental assessment (SEA) and EIA is that EIA is generally used for the individual projects while SEA informs a wider, higher, earlier, more strategic tier of decision-making. EIA documents are more detailed but normally less quntitative than SEA ones. The types of impacts evaluted in EIA can be categorised into:

- Physical and socio-economic;

- Direct and indirect;
- Short-term and long-term;
- Local and strategic (including regional, national and beyond);
- Adverse and beneficial;
- Reversible and irreversible;
- Quantitative and qualitative;
- Actual and percieved;
- Relative to other development, or cumulative (Glasson et al., 2012).

The acceptance and application of EIA depends on the institutional framework and the political context in the country or region (Ortolano et al., 1987). One of the results of the EIA process is the Environmental Impact Statetment (EIS), in which environmental impacts are identified, described and evaluated. The main phases and components of the EIS are described in table 2.5.

Table 2. 5. Phases and components of the EIS (adapted from Toro et al., 2013).

Phase	Component	Description
1. Prelimenary decisions	Project screening Scoping	Decide wether the project requires and EIA List the impacts to be considered, specify the content of the EIA
2. Basic information	Description of the project/actions and alternatives Description of the environmental baseline	Describe different phases and activities of the project alternatives Describe the environmental factors in the area affected by the project
3. Prediction of impacts	Identification and assessment of environmental impacts	Prediction and evaluation of the environmental impacts
4. Environmental management plan	Environmental management plan/design of corrective measures	Propose measures that will prevent or mitigate the potentially significant impacts
5. Monitoring and control	Monitoring and control	Verification of the environmental management plan or the plan of corrected measures

2.8.4. Strategic Environmental Assessment.

Sadler and Verheem (1996) define SEA as a systematic process for evaluating the environmental consequences of proposed policy, plan or programme initiatives in order to ensure they are fully included and appropriately addressed at the earliest possible stage of decision making in the same way as economic and social aspects. Riki (2010) argues that the main aim of SEA is to help to integrated evnironmental (or sustainability) issues in decision-making.

There are numerous documents and regulations worldwide advising on how to integrate environmental aspects into strategic decision-making. However, there is a common agreement on some basic principles of SEA (Hales, 2000). First, SEA is a tool that should be used at the early stages of the decision-making process and concentrate on identifying potential options and changes to the strategic action. Second, SEA should promote participation of other stakeholders, typically including the public. Third, to fit into the timescale and resources of the decision-making process, SEA should focus on key environmental/sustainability constraints, thresholds and limits at the right stage of the planning process. It should not have to be a detailed Environmental Impact Assessment (EIA) review or a collection of baseline data, but has to include key issues. Fourth, SEA should help to identify the best option for the strategic action. Finally, SEA should aim to minimise negative impacts, optimise positive ones, and compensate for the loss of valuable features (Riki, 2010).

2.9. Computer-based modelling.

2.9.1. The purpose of computer-based models.

A large number of sustainability assessment tools have been developed and applied in practice. However, many of these tools are retrospective and can only assess what has already happened in the past. They are useful to see the progress towards the target and to identify the weak areas but they cannot estimate the future trends, uncertainties and changes.

The application of computer-based models in sustainability assessment is very common. A vast amount of models that could estimate the future trends of the economic and environmental aspects of sustainability have been developed. For example, water pollution due to a certain volume of discharge could be modelled as well as the costs of environmental clean-up or building a water purification plant prior to discharge. Some models are very simple; others are much more complex with a large number of variables and parameters. Some models could be very strong conceptual tools but do not have the ability to measure the quantitative outcomes. Others could give the numerical answers but would not have the effective theoretical clarification. The type of the model and its characteristics would depend on many factors such as the scope and type of the project, the purpose of the sustainability assessment, the stakeholders involved, etc. Large unique projects would need many various models and assessment tools to estimate all possible risks and uncertainties. Small projects might only need a few simple models as the outcomes could be estimated effortlessly based on the previous experience of similar projects.

2.9.2. Classification of models.

There are several types of sustainability development models. Todorov and Marinova (2011) distinguish five major categories:

- Pictorial visualisation models;
- Quantitative models;
- Physical models;
- Conceptual models;
- Standardising models.

Pictorial models, such as flow charts and diagrams are simple and basic static models for a broad audience. Conceptual models have long-term and intergenerational perspective and often linked to a political agenda. Standardising models are based on the development and use of sets of various sustainability indicators. These sets are then used to develop a holistic or aggregate sustainability indicator. Physical models are widely used for assessing environmental aspects of sustainability, such as water and energy use, land and air pollution, toxicity, waste management, building and urban design, etc. They reduce uncertainty and allow interdisciplinary perspective.

Quantitative models are based on mathematics, statistics and system analysis. They are more informative, accurate and potent for investigation, forecasting and policy-making (Todorov and Marinova, 2011).

2.9.3. Optimisation models.

Any decision-making process is orientated towards identifying an optimal solution out of the number of the proposed alternative options. Some problems are relatively straightforward and could be solved by simple calculations; others are more sophisticated and require complex computer models to estimate the potential effects of different alternatives. The problems that have an objective function to optimise (for example, to minimise pollution or to maximise profit) in addition to satisfying the requirements on the decision variables are called optimisation problems. All the constraints, boundaries and relationship between variables can be expressed as mathematical equations and then written in a computer language. There are many different types of optimisation problems and the choice of the optimisation technique depends on the problem being solved.

Optimisation technique is a way to determine the best solution from a set of possible alternatives in regard to certain criteria. An optimisation problem can be mathematically formulated by identifying a set of parameters, variables and equations in order to minimise or maximise the objective function. The most common types of the optimisation problems are linear (LP), non-linear (NLP), mixed integer linear (MILP) or mixed integer non-linear (MINLP).

A mixed-integer optimisation problem (MIP) can be formulated as follows (Grossmann et al., 2000):

$$\begin{aligned}
&\min Z = f(x, y) \\
&\text{s.t.} \quad h_i(x, y) = 0 \quad i = 1, \ldots, m \qquad (2.14) \\
&g_i(x, y) \leq 0 \quad i = 1, \ldots, l \\
&x \in X, \; y \in \{0,1\}
\end{aligned}$$

where $f(x, y)$ is the objective function to be optimised (e.g. cost); $h_i(x, y) = 0$ are the equations that describe the performance of the system (e.g. mass and energy balances, design equations); $g_i(x, y) \leq 0$ are inequalities that define the specifications or constraints for feasible choices (e.g. materials availability, energy requirements). The variables x are continuous and generally correspond to the state or design variables, whilst y are the integer variables, which generally are restricted to take 0-1 values to define the selection of an item or an action (Grossmann et al., 2000).

A mixed-integer programming model corresponds to a mixed-integer linear (MILP) or mixed-integer non-linear (MINLP) programming model depending on whether the functions are linear or not. If there are no integer variables, the mixed-integer programming problem reduces to a linear program (LP) or non-linear program (NLP) depending on whether the functions are linear or not (Pieragostini et al., 2012).

Traditionally, system optimisation applications have focused only on a single objective, which was typically to maximise or minimise a certain economic objective function. Over the past two decades, the environmental impacts started to be integrated into system optimisation alongside economic objectives (Azapagic, 1999). Economic objectives, however, are often in conflict with environmental objectives. Thus, multi-objective (MO) optimisation problems started to evolve which assist with solving the trade-offs between the economic and environmental objective functions.

In general, a multi-objective (MO) optimisation problem can be formulated as follows (Guillén-Gosálbez et al., 2008):

$$
\begin{aligned}
&\min f(x,y) = [f_1, f_2, \ldots, f_p] \\
&\text{s.t.} \quad h_i(x, y) = 0 \quad i = 1, \ldots, m \qquad (2.15) \\
&g_i(x, y) \leq 0 \quad i = 1, \ldots, l \\
&x \in X \subseteq R^n \\
&y \in \{0,1\}
\end{aligned}
$$

where constraints are equivalent to those summarised in (1). In this case, the system is optimised simultaneously on a number of objective functions f_1, $f_2 \ldots f_p$ to determine the multidimensional non-inferior or optimal solutions of the problem and represent the points where improving one objective will result in worsening all over objectives (Ngatchou et al., 2005; Guillén-Gosálbez et al., 2008).

Different approaches have been developed in order to solve multi-objective optimisation problems. The two most common approaches are weighted method and ε-constrained method. Weighted method requires participation of decision-makers during the solution process. Decision-makers apply different weights to different criteria and then the problem is solved as a single-objective optimisation model. In ε-constrained method, all objectives except one are treated as a constraint, thus the model is solved as a single-objective model (Gurel and Akturk, 2007; Guillén-Gosálbez et al., 2008). Then the same procedure is repeated for other objective functions and a non-inferior optimal Pareto curve (Figure 2.10) or surface (Figure 2.11) of all possible solutions is presented to decision-makers for consideration. Thus, when ε-constrained method is applied, participation of stakeholders is required when a set of solutions has been obtained and the key stakeholders have to determine only one optimal solution.

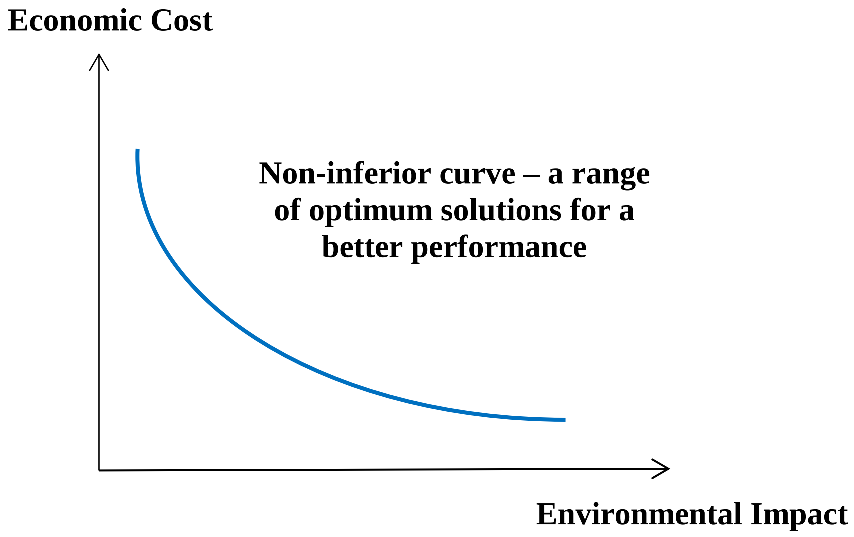


Figure 2. 10. Non-inferior Pareto curve obtained in multi-objective optimisation (2 objective functions) (adapted from Azapagic, 1999).

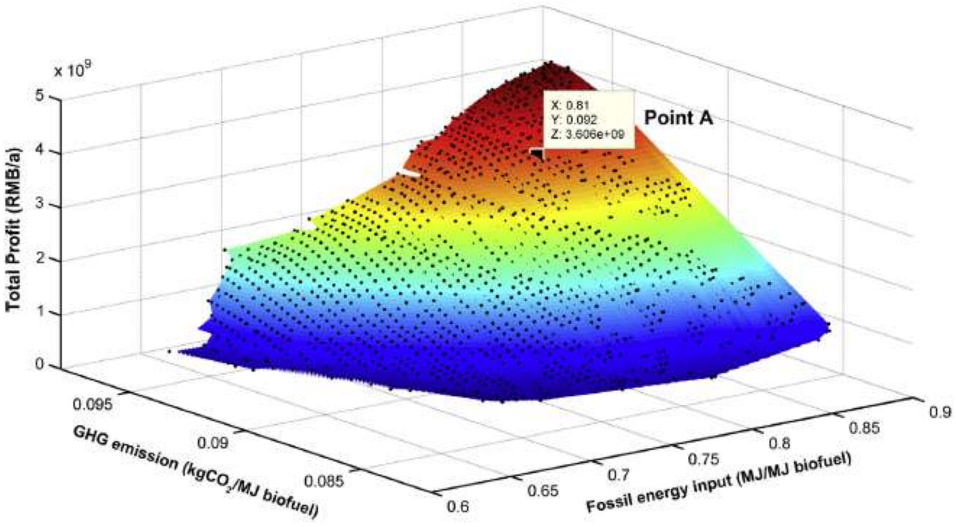


Figure 2. 11. Pareto optimal solution surface obtained in multi-objective optimisation (3 objective functions) (adapted from Liu et al., 2014).

Optimisation techniques provide a valuable tool for decision-making. Any business or industrial process should be optimised in order to reduce costs and maximise the outcome (production of goods and services). The models can significantly assist in choosing the best alternative by optimising a large number of various parameters. Optimisation is a tool that is used in sustainability assessment, particularly when multiple and complex trade-offs between many parameters are involved. Environmental impacts, economic and social benefits and losses could be optimised by modelling a number of alternative scenarios, performing sensitivity analysis and identifying the optimum solution that satisfies the most criteria.

2.10. Summary.

A number of sustainability assessment tools have been developed in recent years and used in the current practice. Some of them are based on the economic and accounting techniques; others concentrate on the evaluation of environmental burdens and socio-cultural impacts. There is no a single standard set of sustainability indicators or assessment tools that can be applied uniformly to all project. The procedure of the evaluation of sustainability aspects varies significantly depending on the type and scale of the industry or business, the scope of the impacts, project life time, involvement and authority of its stakeholders and many other factors. All tools have some advantages and drawbacks; therefore, choosing a set for a particular project, especially for a large unique project is a complex task that requires careful consideration and participation of many stakeholders. Some of the most common SA tools were described in this section and the summary that points out the main advantages and drawbacks is provided in table 2.6.

Table 2. 6. Advantages and drawbacks of the major SA tools (Jeswani et al., 2010; Kissinger and Rees, 2010; Chambers and Lewis, 2001, Torío and Schmidt, 2010, Bebbington *et al.*, 2007, Todorov and Marinova, 2011).

SA Tools	Advantages	Drawbacks
Material Flow Analysis (MFA)	- Accounts for material and energy inputs and waste outputs associated with an entire specified system. - Combines a large amount of data on the materials required for particular economic activities.	- Not suitable for the optimisation of single production systems. - Directed towards reducing the number of substances of study as much as possible to maintain transparency and manageability, which could lead to incomplete evaluation. - Addresses only one dimension of sustainability (environmental).
Life Cycle Assessment (LCA)	- Calculates the environmental burdens and impacts of all elements of the system. - Identifies the “hot spots” and improvement options. - Identifies more environmentally sustainable options. - Aims for completeness in assessing as many as possible substances and compounds.	- Considers only one dimension of sustainability. - Needs integration of social and economic aspects. - Time and location-independent. May lead to inaccurate results in comparative studies.
Environmental Impact Assessment (EIA)	- Unlike LCA, takes into account time-related issues, the specific local geographical situation and	- Due to the lack of data and subjective evaluation of impacts the results can frequently be doubtful.

	the existing pressure on the environment. - Provides qualitative assessment of "soft" issues such as landscapes, cultural assets, etc. - Requires participation of the public and other stakeholders in the process.	
Strategic Environmental Assessment (SEA)	- Similar to EIA, but operates at "higher" levels, i.e. for strategies and policies. - Facilitates environmental as well as broader sustainability policy integration in every political and strategic decision.	- Conducted at the early stages, therefore more uncertainties involved due to less data. - Illustrates only general trends for environmental and social impacts.
Ecological Footprint Analysis (EFA)	- Does not only quantify the energy and materials demand but also the land/waterscape required to supply them. - Can be used to highlight the study population's trade-based dependence on distant ecosystems. - Can interact with MFA and LCA.	- Aggregation can oversimplify impacts due to assumptions and insufficient data. - Focuses more on recourse consumption than on pollution. - Purely environmental tool, does not consider social and economic factors.
Multi-Criteria Decision Analysis (MCDA)	- Tends to be more transparent than other methods, such as CBA due to more clear and specified objectives. - Integrates social, environmental and economic aspects of sustainability. - Effective for the evaluation of complex sustainability issues. - Incorporates qualitative and quantitative data, counting monetary and	- May be time consuming, particularly when multiple stakeholder perspectives are necessary.

	non-monetary aspects. - Criteria result from multiple objectives and may be weighed differently by various groups (which in some cases could be considered as a drawback).	
Energy/exergy analysis (EA)	- Can measure both the quantity of energy (energy analysis) and the quality of energy – the maximum amount of work that can be theoretically obtained (exergy analysis). - Can help to understand the effectiveness of resource utilisation. - Can help to identify the potential areas of technological improvement. - Can be used both on micro, meso and macro levels. - Can be integrated with life cycle approaches.	- There is a risk of concentrating too much only on the energy issues and leaving out other important factors. - Exergy analysis may not be useful for non-energy systems. - If the whole production chain or the interaction with natural ecosystems is excluded, the benefits of exergy analysis for environmental decisions are significantly decreased.
Risk Assessment (RA)	- Focuses on specific harmful endpoint arising from the product or activity. - The results are defined in time and thus provide information regarding the timing of impacts.	- Unknown factors can lead to unknown risks. - The results are more prone to public distrust due to the complexity of issues. - Potential for subjectivity of the assessors and under- or over-estimation of risks due to multiple uncertainties.
Cost Benefit analysis (CBA)	- Easy to understand and interpret the results. - Presents the results as a single criterion – money – that can be easily communicated. - CBA can be used for weighing the social costs	- A common measurement has to be used, which is not always possible particularly when comparing quantitative and qualitative benefits. - The monetization of all values can be highly

	and benefits of various alternatives. - Can consider the time horizon of effects by discounting future costs and benefits.	relevant. - The results of valuation are heavily dependent on the identification of the major stakeholders. -The uncertainty about the discounting the future value and discount rates.
Computer based modelling	- Exact, informative and powerful for analysis and forecasting. - Support policy-making. - Reduce uncertainty. - Allow for a participatory approach and interdisciplinary perspectives.	- Can be restricted. - Remains discipline dominated. - Very specific and predominantly local models. - Their time span is quite restrictive.

Sustainability assessment is a complex task that involves assessment of numerous economic, environmental and social aspects and interactions between them. The choice of an indicator set and evaluation tools depends on the type and scope of the project and requires involvement of many stakeholders and decision-makers. Not all SA tools address all aspects of sustainability in the same way. Some tools, such as LCA, Material Flow Analysis, or Environmental Impact Assessment stand out for their well-developed and comprehensible assessment of environmental impacts. Other tools, such as CBA seem to be the most useful tool in regards to the economic assessment (Buytaert *et al*., 2011).

Quantitative and physical computer based models can be very precise and informative, but it is argued that they can be restricted, very specific models that remain discipline dominated (Todorov and Marinova, 2011). MCDA is probably the most useful existing tool because it has the advantage of incorporating both qualitative and quantitative data and count monetary and non-monetary aspects into the assessment process, thus allowing decision-makers to include a full set of economic, social and technical criteria (Ness *et al*., 2007).

The choice of SA indicators and tools depends on the purpose of the assessment. Retrospective indicators and tools that quantify historical conditions, targets and standards are mostly used for the evaluation of existing projects or operations. Predictive tools and indicators are generally used for the proposed projects to estimate various options of the potential social, economic and environmental benefits and burdens of the project and to choose the best alternative.

Although a number of SA tools have been developed and incorporated into practice in the last few decades, sustainability evaluation and reporting often remains a very difficult task. This is due to the complex interactions of the economic, environmental and social aspects and the trade-offs that have to be considered during the planning process. Sustainability assessment is particularly difficult for large-scale projects such as mega-event projects because of their scope, duration, and a vast array of different stakeholders. Chapter 3 provides a review of the recent studies which addressed various aspects of impact assessment of mega-events. This chapter also provides a summary of sustainability and environmental standards and guidelines that are now widely used when planning a mega-event and reporting the progress towards sustainability goals and targets.

Chapter 3. Impact assessment of mega-event projects.

This chapter presents the main findings from the recent studies on the subject of impact assessment of mega-events. It starts with a review of the publications on the economic assessment followed by a review of the studies which address socio-cultural impacts of mega-events. The next part analyses different techniques that have been used for the environmental evaluation of mega-events and specifies several sustainability standards which are currently used to assist event organisers during the event planning process. The last part provides a summary of the recent studies addressing post-event legacy and explores different legacy categories.

3. 1. Economic impacts assessment of mega-events.

Impact assessment of mega-events on their host cities have been a major topic of the event studies for decades. Previously, most studies primarily addressed economic impacts and analysed how mega-events effect employment, tourism and infrastructure development in a host city. This section provides a review of some recent studies that focus on the economic evaluation of mega-events.

Andreff and Szymanski (2006) examined numerous aspects regarding the economic impacts of sporting events such as construction of the sporting facilities, employment in sport, attendance at sports events, governance and governing bodies in sport, media coverage and broadcasting, international trade in sports goods and other aspects. They discussed the uncertainties of the economic outputs of various sports events and financial innovations in professional and team sport.

Maennig and Zimbalist (2012) investigated the economic and political aspects of mega sporting events such as the Olympic Games, Commonwealth Games and FIFA World Cup. They analysed the bidding process for mega-events, design aspects, and the economic impacts, costs and benefits associated with the organisation of large sporting events. They argue that in many cases the organisers of mega-events typically fall behind in their timetable which results in substantial increase of costs. They also point out that it is very hard to determine if a mega-event had a positive, lasting impact on tourism of a host country (Maennig and Zimbalist, 2012). In fact, the outcomes of some studies determined that the long-term impact on tourism from hosting the Summer Olympics is negative, while the Winter Games show no impact on either tourism or exports (Matheson, 2008; Song, 2010).

Preuss (2004) investigated economics and finances of the Olympics comparing the Games of 1972 – 2008. He analysed the growth and financial gigantism of the Olympic Games in terms of the scale of the investments, revenues and expenses of the Organising Committee (OCOG) and employment opportunities in the host city during and after the Games. He said that the economic aspects of the Olympic Games are very complex and the differentiation derived from macroeconomics and business-economic implications make them even more complicated. He also argued that although the International Olympic Committee (IOC) has a strong influence over the financing sources of the Organising Committee, the expenditures of the OCOG strongly depend on the national conditions of the host city such as the real estate market conditions, level of consumer confidence, salaries and employment, national economic conditions. Preuss (2004) says that the differences in the allocation of expenditure items, in valuations and in the temporal delimitation make it virtually impossible to carry out a comprehensive and rigorous comparative analysis of expenditures of different Olympic Games.

Lee and Taylor (2005) investigated the economic impacts associated with foreign tourism during the 2002 FIFA World Cup in South Korea, using an input-output estimation method excluding tourists whose travel was non-event related. They estimated that direct expenditure of the foreign World Cup tourists was 1.8 times higher compared with the foreign leisure tourists. They propose a methodology that can be used by the policy makers and organisers of similar events in the future to determine the tourists' expenditure.

Daniels and Norman (2003) conducted a study of seven regular sport tourism events by collecting data on average per person per day expenditures at the host cities, which were then translated into total direct and induced effects via input-output modelling. They identified that regular sport events offer great potential for host cities as they normally entail little burden on public funds and low bidding expenses, utilise existing infrastructure and have a negligible impact on local residents.

However, they argue that the impacts and expenses of mega-events are much larger than those of the regular sports events. Therefore, the debate surrounding economic evaluation of mega-events is likely to increase in the future.

The key outcome of the studies reviewed is that the evaluation of economic costs and benefits of a mega-event is a very controversial issue. Some authors claim that mega-events have a positive impact on tourism and expenditure in the host city while others suggest that the impact is minimum or even negative. Expenditure and revenues of the OCOG strongly depend on the strategic plan of a host city, private and public interests and other financing sources available to the OCOG. Moreover, it is argued that a standardised accounting system which allows comparison of expenditures of different OCOGs is missing and the IOC should introduce 'principles for the accounting of the Olympic Games' as a uniform planning instrument (Preuss, 2004).

3.2. Socio-cultural assessment of mega-events.

The triple bottom line (TBL) approach has recently been applied in the planning process and sustainability evaluation of many projects and enterprises including mega-events. TBL is a holistic reporting tool that adds social and environmental lines to the traditional financial bottom line. TBL has lately been revised to integrate social and cultural impacts (Getz, 2009; Lundberg, 2011). Hence, socio-cultural and environmental aspects of mega-events have recently received greater attention and many studies have been conducted by the academic researchers and practitioners in order to assess these aspects.

A large part of the socio-cultural studies investigated the relationship between the local residents' perceptions of mega-events impacts and the level of their support for the events (e.g., Kim et al., 2006; Waitt, 2003; Kim and Petrick, 2005; Ritchie et al., 2009; Lorde et al., 2011; Ohmann et al., 2006; Bob and Swart, 2009; Zhou and Ap, 2009; Gursoy and Kendal, 2006). The outcomes of the studies show that residents perceive the event impacts as either negative or positive, or develop a 'net effect' latent variable (e.g. positive impacts minus negative impacts). The results of the studies also show that there is still much uncertainty about the relationship between residents' overall attitude and the measurement of support. For example, it is obvious to predict support of a mega-event if local residents view most of the event' socio-cultural outcomes as positive. However, if they are imposed to pay additional local tax, their attitude towards the event and, therefore, support may change dramatically (Prayag et al., 2013; Zhou and Ap, 2009; Andereck and Vogt, 2000).

Studies analysing residents' support for events are typically based on the application of the social exchange theory (SET) to the residents' surveys (Andereck and Vogt, 2000; Dyer et al., 2007; Zhou and Ap, 2009). SET has been predominantly effective in explaining residents' support due to its ability to account for different views based on the empirical and psychological outcomes. SET is useful because it accounts for positive and negative impacts simultaneously (Prayag et al., 2013). In terms of the positive impacts, hosting of mega-events promotes the image of a city as a tourist destination, helps people to understand different cultures, brings the community together, builds national identity and strengthens cultural values and traditions (Zhou and Ap, 2009; Kim et al., 2006; Kim and Petrick, 2005; Lorde et al., 2011). In regards to the negative impacts, mega-events can result in crime rates, congestion and crowding, vandalism and conflicts between local residents and visitors. Mega-events can also result in displacement of local residents and disruption of residents' quality of life (Bull and Lovell, 2007; Bob and Swart, 2009; Ritchie et al., 2009; Deery and Jago, 2010).

Generally, the results of many studies on the socio-cultural impact assessment of mega-events show that the overall residents' attitude and support are often determined by many different factors rather than only by the social aspects. Economic factors and willingness to pay certainly play a major part in defining residents' attitude towards a mega-event. Environmental aspects are also equally important as the impacts associated with the construction and demolition of the venues and staging the event are often viewed as negative by the residents and create hostility towards a mega-event.

3.3. Evaluation of the environmental impacts of mega-events.

Environmental impact analysis has become an essential part of a planning process of mega-events. Today, the organisers of mega-events develop environmental strategies as a part of the overall sustainability policies. They specify the actions that are going to be implemented in order to minimise negative environmental impacts resulting from the preparation and staging the event. The range of such actions has expanded significantly in the last decade. Planting trees to offset GHG emissions was one of the earliest environmental actions. For example, the 'Plant it Green: The Global Trees Race' campaign was launched for the 2002 Salt Lake City Games and as a result, more than 100,000 trees were planted in Utah. Additionally, energy recycled from the curling venue was used to heat the showers and bathrooms. For the 2004 Athens Games, over 12,000,000 trees and bushes were planted (CCI, 2014).

Later on, more comprehensive environmental strategies started to advance based on the national and international environmental standards and guidelines. The 2006 Turin Organising Committee was the first Olympic planning group to be granted an ISO 14001 International Environmental Standard Certification for investing in the reforestation and renewable energy projects to offset GHG emissions from the Games. Beijing introduced a range of new sustainable venue designs to the Olympic Park and Village saving approximately 1.2 million tons of CO_2. The 2010 Vancouver Olympics also implemented innovative sustainable venue design and as a result the Olympic Village and surrounding areas received LEED (Leadership in Energy & Environmental Design) Platinum rating certification (CCI, 2014). Apart from the Olympic Games, environmental strategies are becoming a fundamental part of the strategic plans of other major events. For example, environmental and sustainability performance reports have been published for mega-events such as the 2006 Melbourne Commonwealth Games (DVC, 2006), 2006 FIFA World Cup (Green Goal, 2006) and UEFA Euro 2008 (ARE, 2008).

The London 2012 Olympic Games organisers also incorporated numerous sustainability and environmental aspects into the Games planning process. Two major organisers of the London 2012 Olympics were the Organising Committee (LOCOG), a privately funded body responsible for promoting and staging the

Games, and the Olympic Delivery Authority (ODA), a publicly funded body responsible for constructing the main venues and infrastructure. The ODA published a ‘Sustainable Development Strategy’ in January 2007 in which it stated how the issues of climate change, waste, biodiversity, healthy living and inclusion will be tackled during the construction phase (London2012, 2007a). The strategy became a part of the overall London 2012 sustainability plan ‘Towards a one planet 2012’ (London2012, 2009), a detailed action plan which also specified sustainability goals for event staging phase. The strategy was developed within the guidelines of the British Standard BS 8901 ‘Specification for a Sustainability Management System for Events’, which provides recommendations on incorporating sustainability into the strategic planning and staging of events. The BS 8901 was first published in 2007 and significantly influenced the development of the ISO 20121 ‘Event sustainability management systems’ published in 2012.

Several other environmental and sustainability standards and guidelines have been developed in the last few decades which are now widely used by multiple enterprises (e.g. ISO14000 (ISO, 2014a), ISO14040 (ISO, 2006a)). The standards have been developed with different aims: some merely provide the instructions on the implementation of various environmental measures, while others define explicit actions that have to be taken by the organisations in order to comply with the certification procedures. Several standards have been developed which provide recommendations and principles specifically for the event sustainability management systems. The overview of the key standards and guidelines currently used in practice is provided in section 3.1.1.

3.3.1. Environmental and sustainability standards and guidelines.

Environmental impacts of mega-events play a significant role in the overall attitude of different stakeholder groups. Thus, a comprehensive strategy on mitigating negative environmental impacts has become an important feature of a planning process. Mega-event planning is a complex multi-staged process, thus, common universal guidelines can significantly simplify the implementation of sustainability measures throughout the whole project life cycle. The most widely applied sustainability and environmental event guidelines and standards are:

- **The Olympic Movement Agenda 21.** It was inspired by the UNCED Agenda 21 and adapted to the characteristics of the Olympic and sports movements. It suggests to the governing bodies and individuals the areas in which sustainable development could be integrated into their policies. The emphasis is placed on sustainable resource and waste management, environmental protection education and training, respect of the different social, economic, geographical, climatic, cultural and religious contexts which are the characteristics of the diversity of the members of the Olympic Movement (IOC, 1999).

- **IOC Guide on Sport, Environment, and Sustainable Development**. It provides event organisers, sports authorities, competitors and the public with detailed environmental guidelines on organising sporting events in regards to the different sports types (winter or summer, indoors and outdoors) (IOC, 2006).

- **ISO 14001-14006 Environmental Management Systems**. The standards that cover the design and implementation of an environmental management systems (EMS). It is a framework which was designed to assist organisations with measuring and improving the use of natural resources and reducing emissions from waste disposal. It is a generic standard which is applicable to any organisation. The benefits of using ISO 14001 can include reduced cost of waste management, savings in energy and materials use, lower distribution costs and improve corporate image among regulators, customers and public (ISO, 2014a).

- **ISO 26000 Social Responsibility**. This standard provides guidance to all types of organisations on the concepts, terms, characteristics, core subjects and issues of social responsibility (SR) and on practices and principles relating to SR. It is intended to assist organisations in contributing to sustainable development and encourage them to consider societal, environmental, legal, cultural, political and organisational diversity. It is not a management system standard and, thus, it is not appropriate for certification purposes or regulatory or contractual use. It does not contain any requirements; it provides guidance concerning SR and can be used as a part of public policy activities (ISO, 2014b).

- **BS 8901 Specification for a Sustainability Management System for Events.** This standard was developed by British Standards Institute. It provides a set of guidelines to help with the planning and management of sustainable events. The requirements of BS 8901 were developed for events of all types and sizes. The standard can be applied throughout the entire supply chain. By applying this standard, event organisers can improve their sustainability within budget, reduce carbon emissions and waste and implement appropriate safety measures (BSI, 2014).

- **ISO 20121 Event sustainability management systems**. Based on the earlier BSI 8901 standard, this management system standard has been designed to help organisations in the events industry to improve the sustainability of their event related activities, products and services. It applies to all types of sizes of organisations involved in the event industry. The standard applies to the management system operated by the organisation that is compliant with ISO20121, not the event. It does not specify which sustainability issues to manage or what performance levels to achieve (ISO, 2012).

- **GRI G3 Sustainability Reporting Guidelines**. Developed by the Global Reporting Initiative, the document provides recommendations on sustainability reporting of all types of organisations. The first part provides guidance and principles for defining report content, quality and boundary setting. The second part specifies the base content that should appear in a sustainability report in terms of strategy and profile, management approach and performance indicators. It also provides a technical protocol on applying the report content principles (GRI, 2011).

The above standards and guidelines have been internationally adopted as the main standards and are being widely used during the planning of mega-events. The investigation of the main standards showed that although they can provide some essential guidelines when developing a sustainability management strategy and reporting the progress, they do not specify any quantitative targets or define a set of tools that should be used in order to measure the company's performance.

A similar conclusion was drawn after analysing a number of toolkits that were developed based on the above standards for specific mega-events. One of them is the 'Sustainable Sport and Event Toolkit' (SSET, 2008) developed by the Vancouver Organising Committee for the 2010 Olympic and Paralympic Winter Games. This toolkit was designed to help with developing a sustainability strategy for the 2010 Winter Olympics and other similar major events. This toolkit provides event organisers with a set of goals in different sections such as transportation, catering, site selection and construction, supply chain, athlete and public engagement. This is a qualitative framework which describes the objectives and provides a recommended list of actions. Some quantitative performance indicators are suggested, however, the toolkit does not provide any suggestions on specific numerical targets and evaluation techniques.

Although the standards provide some useful recommendations for the event organisers, sustainability management strategies of different mega-events vary considerably. The main reasons are the common concentration of the organisers on local issues of the host cities, a complexity of trade-offs between sustainability aspects, and a mixture of qualitative and quantitative performance indicators. It is argued that currently there is no a common standard or a uniform system that could be applied for a holistic quantitative assessment and comparison of the sustainability impacts of mega-events (Collins et al., 2009).

3.3.2. Quantitative assessment of the environmental impacts of mega-events.

Present environmental guidelines and standards may only provide event planners with partial information for the implementation of certain actions. Therefore, there is a need for a framework that can be used to measure various environmental criteria in numerical terms which allow a comparison between mega-events or against any notional 'best case' scenario (Collins et al., 2009). Although such a uniform quantitative framework has not yet been introduced into a mega-event planning procedure, a number of tools which can quantify environmental impacts have been developed and applied in practice.

Environmental evaluation has received an increasing interest within the field of event studies in the last two decades (e.g. Dolles and Södermann, 2010; Ponsford, 2011; Collins et al., 2009). Ecological footprint analysis is one of the most frequently used tools for measuring environmental impacts of mega-events (Collins et al., 2007; Gössling et al., 2002; Gössling et al., 2005; Hunter, 2002; Hunter and Shaw, 2005). In such studies, the ecological footprint of the event is normally calculated based on a component approach including travel of visitors to and from the event, food and drink consumed at the event, materials and energy used during the construction and operation of the infrastructure of the event venues, waste generated at the event and so on. The total footprint is estimated as the area of bioproductive land required to support the demands of a reference area that can be compared to a global average of approximately 1.8 global hectares per capita. It is argued, however, that the ecological footprint reveals a more global estimate of impacts and, therefore, it should be combined with other tools to permit an evaluation of the within-nation environmental impacts (Collins et al., 2009).

Another method of assessing the environmental impacts is the evaluation of greenhouse gas emissions (GHG) caused by different activities during the construction and staging of a mega-event. The total amount of all (GHG) emissions resulting from a process, event or service is called ‘carbon footprint’. Carbon footprint is calculated as carbon dioxide equivalent (CO_2-eq) using the relevant 100-year global warming potential (GWP) of different types of greenhouse gases. GWP is a relative measure of how much heat a GHG traps in the atmosphere (Porteous, 2008).

A number of studies have been published which provide the results of carbon footprint calculations of different mega-events. One of them is an independent carbon footprint study for the 2008 Beijing Summer Olympic Games which was published by the United Nations Environmental Programme in 2009. This study provides a summary of the GHG emissions from the construction and operation of the venues, travel of the international spectators, media, athletes and Olympic family, operation of the Organising Committee, visitors' accommodation, waste treatment and torch relay. The study also shows the breakdown of avoided emissions resulting from using clean fuels, solar energy power and hot water generation, green lighting system and geo-thermal heat pump during the Games period (UNEP, 2009).

Another study was published in 2007 by the LOCOG for the 2012 London Olympic Games which estimated potential carbon footprint of the Games (London2012, 2007b). This comprehensive study provides the estimated GHG emissions from the construction and operation of the venues, transportation of visitors, waste and materials, merchandising, catering, accommodation, torch relay and other activities. After the event, the carbon footprint of the Games was calculated again based on the real data. The results were published by the LOCOG in December 2012 in the post-Games sustainability report 'A legacy of change' (London2012, 2012). The outcome of the report show that the total actual measured carbon footprint of the Games (including construction of the Olympic Park and staging the event) was 3.3 million tonnes of CO_2-eq against the original estimated reference value of 3.4 million tonnes of CO_2-eq. The report also provides a breakdown of the total emissions to demonstrate those areas where the most emission savings were achieved.

The outcomes of the recent studies and publications on the evaluation of environmental impacts of mega-events demonstrate that significant progress has been made in the last decades and a number of tools such as ecological and carbon footprints are now widely used for environmental assessment of mega-events. It is also recognised that environmental impacts of the Games should not only include those associated with the activities during a short period of the actual event staging, but also those resulting from a much longer preparation and construction phase. It was estimated that more than 60% of the total GHG emissions for the London 2012 Olympics are attributed to the construction of the venues and transport infrastructure (London2012, 2012).

Almost all of the reviewed studies accentuate the importance of integrating the impacts from both construction and event phases for a holistic impact assessment. However, the majority of them do not mention the other phase of a mega-event project, which is the longest and, perhaps, the most important one – the post-event legacy. For many years, mega-event legacies were associated with specific sport-related activities in the post-event period or with a tourism legacy (Kasimati, 2003; Cornelissen, 2004; Li and McCabe, 2013). Lately, however, the importance of more wide-ranging post-event legacy types has been strongly emphasised by the organisers of mega-events and authorities of the host cities (Frey et al., 2008).

3.4. Definitions, types and evaluation of mega-event legacies.

In regards to the largest mega-event, the Olympic Games, the significance of securing a lasting legacy created by the Games has been recognised by the International Olympic Committee (IOC) since the 1990s. The IOC identifies the importance of the Games legacies in the Rule 2 of the Olympic Charter which declares ‘to promote a positive legacy from the Olympic Games to the host cities and host countries’ (IOC, 2007). It is now often stressed that the candidate cities should be evaluated on the environmental consequences of their plans and sustainability assessment should focus on the long-lasting legacy (Gold and Gold, 2011).

The concept of legacy has rapidly become a vital part of the bids and subsequent organisational strategies of other mega-events. The growing popularity of the sustainability concept led to the need for a holistic evaluation of a mega-event including social and environmental legacies alongside the economic ones. One of many definitions of a mega-event legacy is ‘all that remains and may be considered as consequences of the event in its environment’ (Chappelet, 2012). The consequences can be positive or negative, planned or unplanned, tangible or intangible (Preuss, 2007). Agha et al. (2012) argue that it is almost impossible to estimate the true costs or benefits that stem from a mega-event because of the complexity of the project, time scale of legacy and vast array of public, private and government stakeholders. Moreover, the same legacy aspect can be seen as both positive and negative depending on the industry. For example, an increased tourism may be seen as a positive economic legacy but negative in regards to the environmental damage. Thus, it is argued that although the triple bottom line is the dominant approach to measure the efficacy of hosting a mega-event, it is unlikely that gains in each of the three areas will be achieved throughout the whole project life cycle (Agha et al., 2012).

There have been many attempts to classify different types of mega-event legacies in order to determine which ones are the most applicable for a specific mega-event and which assessment techniques could be used. Table 3.1 provides a summary of the main legacy categories.

Table 3. 1. Main categories of mega-event legacies (adapted from Cashman, 2003; Chappelet, 2003; Hiller, 2003; Gratton and Preuss, 2008; IOC, 2009; Agha et al, 2012).

Legacy category	Indicators and metrics
Culture and education	Cultural exchange, architecture, ceremonies, art, museums, memorabilia, monuments, memories, souvenirs, street names, torch relay
Economic	Economic activity, employment, profits, costs, debts, investments
Environment and sustainable development	Increased traffic and air pollution during construction and preparation, investment in public transport, increased cycling routes and pedestrian zones, new wildlife and eco-system conservation, waste minimisation
Intangibles	Collective effort and memories, disability awareness, experience and learning, inconvenience for local residents, joy, community cohesiveness, volunteering
Built infrastructure	New airports, roads, railways, public transport links, traffic management systems, fibre optic networks, water and energy networks, buildings
Sports	Increase in local recreational or competitive physical activity, post-event Olympic venues use for sports events
Real estate	Short-term boost to rentals and prices, long-term increase in house prices
Tourism and convention industry	Growth in city marketing, convention delegates, general tourism, quantity and quality of hotel facilities, convention space
Urban regeneration	Land regeneration projects, renovation of buildings, venues conversion for a wide variety of new uses

Various types of legacy will affect different people in different ways (Davis and Thornley, 2010). For example, sports legacy will not be considered important by those who are not sports activists and unlikely to ever attend any of the Games events or the post-event sports competitions in the Olympic Park. Another example is the urban regeneration projects. Such projects often lead to a substantial improvement of socially and environmentally deprived neighbourhoods. In many cases, however, it also leads to the involuntary relocation of the local residents who will not benefit from such projects. Thus, it is argued that in order to investigate legacy, it is necessary to disaggregate the concept and evaluate various legacy aspects on different stakeholder groups (Davis and Thornley, 2010).

A number of studies have recently been published that attempt to evaluate different types of mega-event legacies. Some authors propose frameworks for measuring socio-economic legacies (e.g., Minnaert, 2012; Lamberti et al., 2011; Prayag et al., 2013); others focused on the evaluation of economics impacts and utilisation of built infrastructure in the post-event period (e.g., Hiller, 2006; Li et al., 2013). A number of conceptual frameworks on measuring legacies of mega-events have been recently proposed in some studies. Most of them, however, focus on the evaluation of potential tourism legacy. For example, Li and McCabe (2013) propose a theoretical framework for measuring various types of legacies of mega-events associated with tourism. In this methodology legacies are divided into three categories: economic, social and compounding. Compounding legacies are defined by the authors as those that do not have a close connection to tourism but can add compounding economic or social effects. The authors identified and elaborated the theoretical aspects surrounding key measures to evaluate a core set of the following indicators:

- Induced tourism;
- Stadiums and facilities;
- Economic activities;
- Social benefits/costs;
- Image level;
- Awareness levels.

The authors emphasise the complexities involved in the evaluation of mega-event legacies. They also point out a lack of a systematic framework that can support event organisers to formulate policies which will enhance legacies (Li and McCabe, 2013).

3.5. Summary.

In this chapter a review of the recent studies on sustainability assessment of mega-events has been carried out. Latest developments in the field of event studies demonstrate that the concept of sustainability has been integrated into the bids for mega-events and the event sustainability strategies. Thus, the earlier focus on primarily economic assessment has shifted towards a broader sustainability assessment including social and environmental aspects. Numerous sustainability and environmental standards and guidelines were developed in the last few decades which now serve as a valuable tool for the development of management strategies for mega-events and setting up sustainability targets.

Most event studies emphasise that the impacts from the construction of the event venues and infrastructure should also be accounted for and included in the holistic impact assessment of mega-events. A number of quantitative tools (e.g. Ecological Footprint, Strategic Impact Assessment) have been investigated which are currently used in practice for the evaluation of the environmental, economic and social aspects of mega-events.

Enhancing positive legacies has recently been recognised as one of the major goals in the event planning. However, while different types of legacies have been identified by many authors, most of the reviewed studies mainly concentrate on the economic impacts of mega-events on the tourism legacy. A few conceptual legacy evaluation frameworks were proposed, however, these frameworks merely suggest which aspects should be considered when planning a mega-event and do not specify how to measure them.

In most of the studies reviewed, a quantitative assessment of mega-events mainly includes the impacts associated with the actual event or the construction of the event venues. There is no such methodology that also includes a comprehensive assessment of the legacy phase that could be used during the planning process in order to assist with identifying the optimum scenario of the post-event site redevelopment and creating a long-lasting legacy.

A review of the recent studies on the sustainability assessment of mega-events provided in this chapter pointed out that there is no a comprehensive evaluation framework that can be used for a holistic sustainability assessment of mega-event projects. A number of studies have been carried out in order to evaluate impacts of mega-events; however, they normally assess a certain aspect, such as tourists' spending, in isolation and generally address only the event phase without considering the long-term impacts of the post-event legacy phase.

In the next chapter, a proposed novel framework for the holistic evaluation of all phases of a mega-event project is presented and a case study is outlined. Chapters 5-7 demonstrate the application of the proposed framework to the social and environmental assessment of mega-event projects. Although economic assessment tools are outlined in the methodology, a complete economic evaluation is beyond the scope of this project.

Chapter 4. Project methodology and a case study.

This chapter begins with the summary of the main features of mega-event projects and the explanation of the complexities associated with planning and implementation of such projects. Then the proposed methodology for a comprehensive evaluation of mega-event projects is presented and its main steps are described. The next part defines a set of sustainability indicators groups and assessment tools applied in the proposed methodology. The final part provides the description of the proposed scenarios of the post-event London Olympic Park developed in this work to test the practicality of the proposed methodology.

4.1. Main characteristics and complexities of a mega-event project.

As defined earlier, a mega-event project is a long-term large-scale multi-billion dollar project with multiple sub-projects of different scope and duration. The ultimate purpose of a mega-event project is the staging of a mega-event such as the Olympic Games or FIFA World Cup. The actual staging of the event only lasts a few weeks; however, the construction phase and redevelopment of the post-event site for the long-term legacy phase take years and have many features of other infrastructure mega-projects. The main characteristics of a mega-project are the following:

- Substantial capital investment;
- Long-term planning and implementation of multiple phases of different duration;
- Development of new infrastructure, utilities and services;
- Complex array of organisational links;
- Significant wide-ranging impacts (geographically and by type: social, economic and environmental);
- Coverage of large areas;
- Employment of large number of people during the construction and event staging;
- Often unique at a national level;

- Embedded in a national political context which can change over time;
- Often involve new and unproven technology and legislation;
- Require special procedures such as complex programme management and cross-functional collaboration, high precision of alighment, planning, coordiantion and execution of the multiple projects and often conflicts of resources and schedules between the projects (Locatelli, et al., 2014; Van Marrewijk et al.; 2008; Sun and Zhang, 2011; Rodney Turner, J., 2014).

Figure 4.1 provides a holistic representation of a mega-event project as a complex system with numerous inputs, such as materials, labour and energy, and outputs, such as infrastructure, employment and services. The activities within the system also cause environmental impacts, which may be both negative and positive.

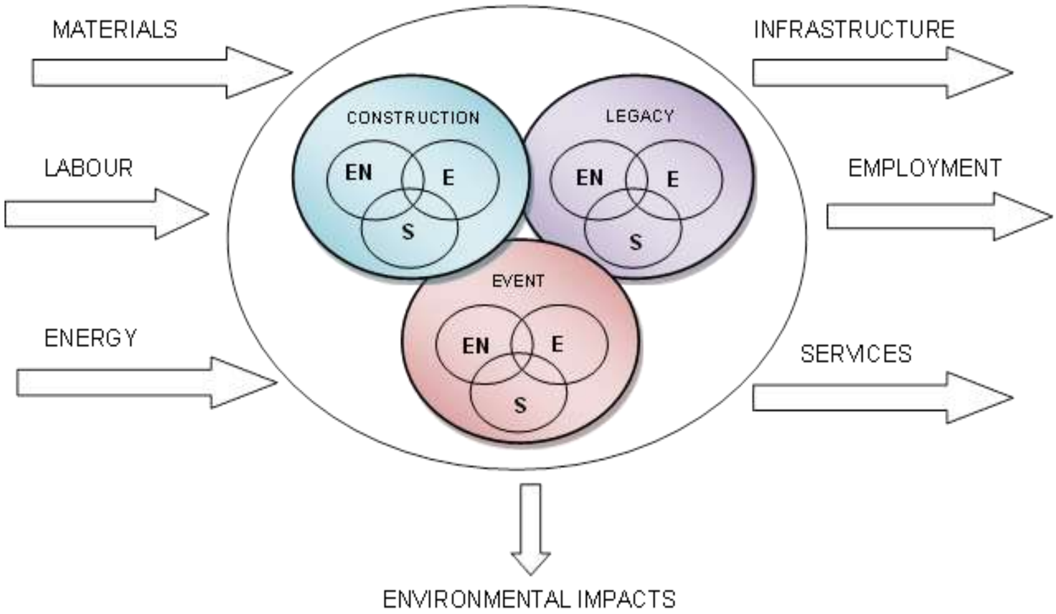


Figure 4. 1. Holistic representation of a mega-event project as a complex system (EN, E, S are environmental, economic and social indicators) (Parkes et al., 2012).

The overall system is divided into three main subsystems according to the phases of a mega-event project: construction, event and legacy. Each of the subsystems consists of other subsystems, which can be thought of as sub-projects of the overall mega-event project. All subsystems are interconnected. Each subsystem also involves a complex interaction of economic (E), environmental (EN) and social (S) aspects that have to be addressed during a planning process. The design phase is certainly the most crucial step because this is when the most significant aspects and various alternatives of the proposed site design scenarios are being developed and evaluated. Decisions taken at this stage will have a long-term effect not only on the event phase but also on the long-lasting post-event legacy.

Early planning of the post-event site redevelopment and its integration with existing urban infrastructure with the neighbouring areas is fundamental to ensure that the project continues delivering on-going sustainable positive impacts long after the event is over. Although the attention of millions of spectators will be focused on the actual event, it is the legacy phase that will be a measurement of the long-term success or failure of the overall mega-event project. Thus, a concurrent planning of the site design scenarios for both the event itself and a post-event legacy should be carried out from the early days of the project in order to identify the optimum design alternatives, minimise financial costs and resource use and maximise the overall long-term benefits.

It is also crucial that a mega-event project is incorporated into a long-term development plan of a host city. Decision-makers must ensure that any measures implemented for a mega-event project form an integral part of a development plan formulated in conjunction with diverse stakeholders and experts groups. Therefore, host cities should shift their focus from the event staging to the post-event phase and sustainability of the overall mega-event project should be addressed in the bidding application.

However, planning of a mega-event project is not a straightforward task. It requires expertise of numerous specialists such as economists, architects, urban planners, engineers, ecologists, event organisers, social scientists, etc. In order to identify which of the proposed site design scenarios is the optimum one, it is necessary to produce quantitative evaluation of the proposed scenarios and present results in a concise and clear way for the consideration of all stakeholders. A thorough sustainability assessment of all design scenarios, however, can be challenging due to the time and resource constraints, uncertainty or unavailability of data and a large number of the potential post-event scenarios. The methodology described in section 4.2 proposes a novel holistic framework for the sustainability assessment of mega-event projects. The methodology takes into consideration all stages of a mega-event project with particular emphasis on the legacy phase. It is an upper-tier strategic impact assessment universal tool that can be used by decision makers and planners throughout the project’s whole life cycle, particularly at the early design stages to estimate potential impacts and optimise design scenarios.

4.2. Methodology.

Figure 4.2 shows a schematic representation of the proposed methodology for a comprehensive evaluation of mega-event projects. It was developed for the initial evaluation of the proposed design scenarios of the event and post-event site development/usage in order to identity, evaluate and optimise the most significant economic, environmental and social aspects of a mega-event project.

The first step of the proposed methodology is preliminary planning and design of alternative scenarios. The evaluation criteria are a set of economic, environmental and social indicators used for the assessment and comparison of the proposed scenarios. A key set of indicators addressing multiple design features should be presented to all stakeholders to determine those that are perceived as the most important ones. These features will become a core of the planning process and will receive priority during the implementation and resource allocation. Once agreed by the majority of stakeholders and decision makers, a complete assessment of the chosen scenarios is carried out. A quantified summary of results is then presented to the decision-makers and stakeholders. If the majority of the key stakeholders agree on a specific outcome, the scenario is then implemented. Otherwise, further changes and assessment will be required with the relevant stakeholders’ consultations. The changes may include modifications of the design scenarios and/or indicators set. The process may be repeated several times until the optimum scenario is finally identified and approved by the majority of actors.

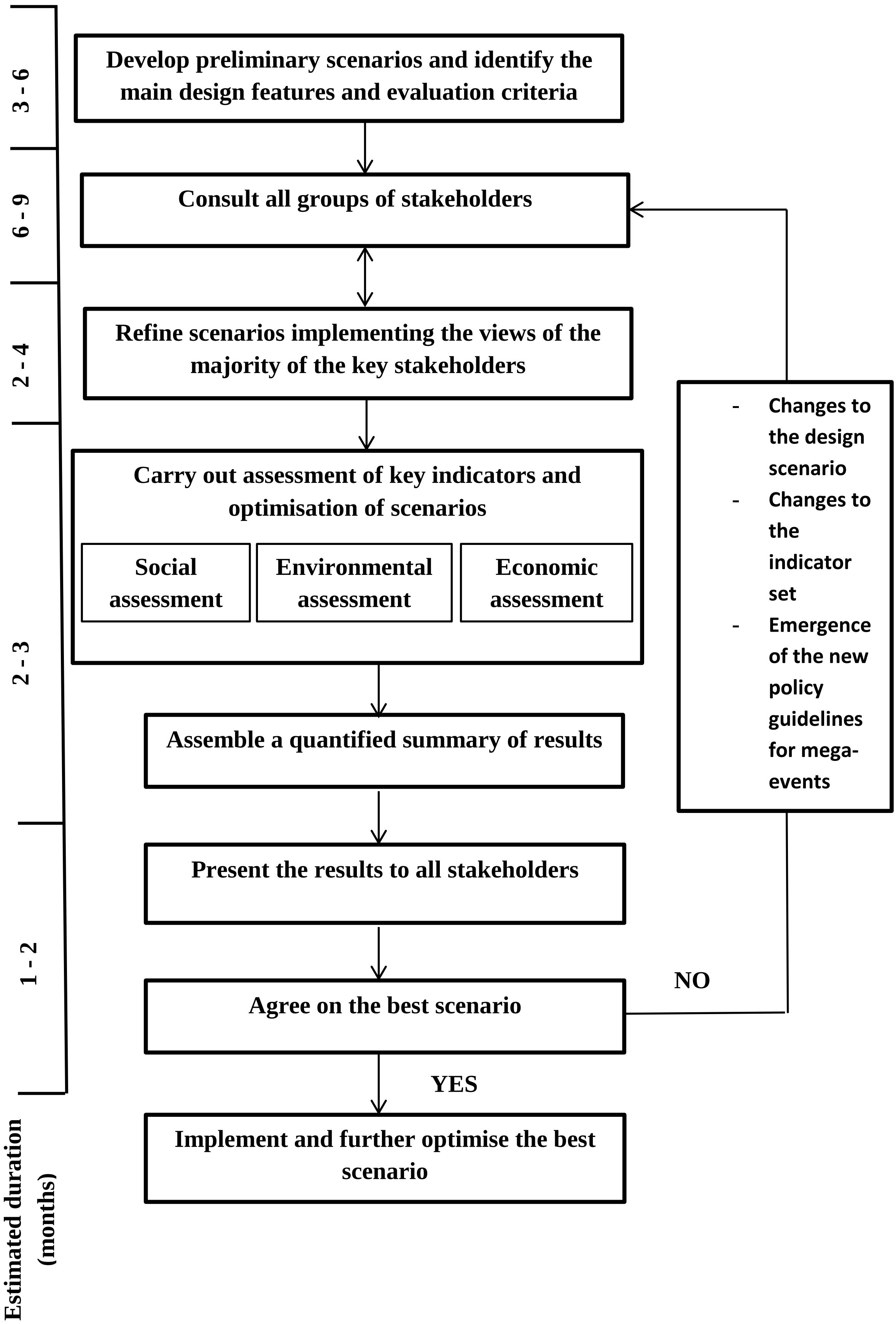


Figure 4. 2. A schematic overview of the proposed methodology for sustainability assessment of mega-event projects.

As mentioned earlier, it is crucial to consider the integration of a post-event site with nearby community areas at the early stages of the project and include the redevelopment of the site into the city development strategy. This will inevitably entail some uncertainties because the bidding phase of a mega-event project generally starts up to 10 years before the actual event takes place and the post-event redevelopment will be completed years later after the end of the event. Thus, it is likely that some changes in the post-event design scenario will be required at a later stage. However, the major features of the site design have to be approved at the earlier stages as they will be the core of the overall long-term project plan.

The main features of the event site design scenarios will be venues, athletes' accommodation, transport infrastructure, green open recreational space and safety and security. The design of the event site will be defined mostly according to the requirements of the organising committee developed specifically for the events of such category and scope. The design of the post-event site, however, does not have any explicit guidelines and will be determined by the city authorities, urban planners and other decision-makers (see Figure 5.1). The main features of the post-event design scenario will strongly depend on the type and size of a proposed development and, therefore, must address a number of questions such as:

- Whether it is going to be a residential, commercial or mixed area?
- What types of houses and/or offices are going to be built?
- What will be the number of potential residents, employees and visitors?
- How many resources will be needed for the site operation (energy, water) and how to provide them in a most sustainable way?
- What are the best waste management solutions for all types of waste generated at each project phase?
- What types of other facilities have to be built on or nearby the site?
- Which venues will permanently be in operation in the post-event site?
- How will a new development affect the eco-system and biodiversity of the site and neighbouring areas?

4.3. Sustainability indicator groups and assessment tools applied in the proposed methodology.

The proposed methodology emphasises the need to address of sustainability aspects: social, environmental and economic, and suggests the tools for their assessment. A part of this work is dedicated to social assessment of mega-event project. However, the main aim of this project is the integrated environmental assessment of all phases of a mega-event project. The environmental evaluation framework includes a combination of computational models which evaluate and optimise the total emissions resulting from the transportation, materials, water and energy use, and a series of LCA models which estimate environmental burdens resulting from municipal solid waste (MSW) management.

A series of the computational models have been developed using General Algebraic Modelling System (GAMS, 2014) a high level modelling system for mathematical programming problems. The models are used to estimate amount of resources (electricity, gas, transportation fuel, water, building materials) and optimise the total emissions (measured in CO_2-eq) of each of the proposed site design scenarios throughout the whole project life cycle. The detailed description of the models, mathematical formulation and the results are provided in chapter 6. The main aspects considered in the models are:

- Transport. Includes emissions resulting from transportation of construction materials and waste during the construction phase, emissions from transportation of visitors, official, athletes, media, and employees during the event, emissions from transportation of potential visitors, residents and employees in the post-event phase. The total emissions can be optimised by providing low carbon transport infrastructure (public transport, electric vehicle charging points, cycling and walking paths) which will be used during the event and particularly in the legacy phase.
- Materials. Includes embodied carbon of building materials resulting from the construction of the event venues and infrastructure and post-event site redevelopment. These emissions can be optimised by using materials

produced on or nearby the event site, by choosing materials with low embodied carbon or by using reclaimed and recycled construction materials.

- Water. Comprises emissions resulting from the supply of water and removal of waste water at all stages of the project. The total emissions can be optimised by maximising the use of non-potable water for construction and irrigation purposes and minimising the use of potable water through the installation of water efficient fittings in buildings and through efficient design of those venues which are identified as the highest water consumers.
- Energy. Comprises emissions resulting from the consumption of gas, electricity and diesel during the construction, event staging, post-event site redevelopment and operation in a legacy phase. The emissions can be optimised by maximising the use of renewable and low carbon energy, installation of energy efficient appliances and through efficient building design.

In the computational models, the quantity of resources throughout the project life cycle is estimated based on the construction materials and methods; number and type of the sports venues and other facilities and availability of different transport modes during the event staging; number, size and category of the residential and non-residential buildings and other amenities in the post-event phase. Then, the total emissions are optimised based on a number of constraints such as supply and demand of materials, energy and fuels, availability of various transport modes, sustainability targets and others. The amounts of municipal solid waste are also estimated in the computational model; however, emissions associated with waste management cannot be estimated in the same model due to the following reasons:

- MSW quantity, composition and recycling rates vary significantly depending on the type, size and location of buildings;
- Same types of MSW can be treated in different waste management facilities;
- Environmental burdens of various waste treatment plants may vary significantly;

- Different MSW waste streams are normally treated at different facilities, thus integrated waste management systems have to be evaluated for the total MSW stream;
- Different integrated waste management systems can be designed for management of the same MSW.

After thorough consideration of the environmental assessment tools and methodologies discussed in Chapter 2, I identified the life cycle assessment (LCA) technique as the most appropriate tool to be applied in this project for the environmental evaluation of the municipal solid waste (MSW) treatment options.

I developed 10 integrated waste management systems (IWMSs) comprising the combination of facilities which reflect the current UK waste management practise and those ones that have a potential to be implemented commercially in the near future, i.e. Advanced Thermal Treatment (ATT) facilities and Anaerobic Digestion (AD). I developed 10 LCA models corresponding to each IWMS using GaBi Product Sustainability Software (GaBi, 2013). The detailed methodology and results of all integrated waste management systems developed in this project are provided in chapter 7.

Social assessment of mega-event projects is a complicated task because it involves a combination of qualitative and quantitative indicators. Qualitative indicators are normally very subjective due to the involvement of a large number of stakeholders who often have different or even conflicting perspectives. Moreover, specific indicator sets are needed to evaluate different phases of the project. Multi-criteria decision analysis (MCDA) (Wang *et al*., 2009) is proposed for the evaluation of the main design features and qualitative social indicators because this is an assessment tool that can combine both qualitative and quantitative, monetary and non-monetary indicators. MCDA can also be applied at the final consultation of the decision makers and stakeholders when determining the most optimum scenario. Although a full social sustainability of all phases of a mega-event project is beyond the scope of this work, chapter 5 explains how MCDA can be applied to quantify the results of the stakeholders' surveys in order to give numerical values to qualitative indicators and allow their comparison. It provides the results of a survey which was developed specifically for this project in order to examine how views of different stakeholder groups can be interpreted in numerical terms and incorporated in scenario planning.

Economic assessment is normally carried out using a cost-benefit analysis in order to estimate economic impacts of a project. Economic evaluation of a mega-event project is not a straightforward task due to the number of actors, time scale of different phases of a project, financing schemes and other numerous factors that have to be considered. In this respect, according to Preuss (2004), the main questions that the organisers of a mega-event have to answer are the following:

- What are the costs and benefits for the residents of the host city?
- What are the financing sources available to the Organising Committee (OC)? What is the estimated amount of the revenues?
- What are the expenditures of the OC? Will it be able to organise a mega-event without a deficit?
- What is the share of the public and private interests when financing a mega-event?
- What is the economic benefit of a mega-event? Is it transitory or lasting?
- How to evaluate an economic legacy?
- How reliable are data on the costs of the past mega-events?
- What costs must be covered by an OC and what factors determine them?

It is clear that economic evaluation of staging a mega-event involves numerous complex issues; therefore, it is a subject of many discussions and research studies. It is a vital part of the overall sustainability assessment of mega-event projects and has to be carried out by the experts in economics. Hence, a thorough economic evaluation of the staging of a mega-event and its economic legacy is beyond the scope of this project.

4.4. A case study – the London 2012 Olympic Park.

A proposed framework for the environmental assessment of mega-event projects has been applied to a case study - the London 2012 Olympic Park. The Park was built as a sporting complex to host the 2012 Summer Olympic and Paralympic Games. It is situated in the east part of London adjacent to the Stratford City. During the Games it was called the Olympic Park which was comprised of 9 temporary and permanent sporting venues, the athletes' Olympic Village, the Broadcast and Media Centre, and the Energy Centre. After the Games, the park was renamed as the Queen Elizabeth II Olympic Park. It occupies an area of 2 km^2 overlapping four east London boroughs: Newham, Tower Hamlets, Hackney and Waltham Forest. It is currently undergoing major redevelopment and parts of the park have started to reopen to the public since July 2013. The sports legacy of the Games is five permanent Olympic sports venues: the Copper box arena, which hosted the handball, fencing and goalball during the 2012 Games, the Stadium, Lee Valley Hockey and Tennis Centre, London Aquatics Centre and Lee Valley VeloPark.

During the preparation for the event and after the Games, a number of reports have been published providing information about the design and construction of the Olympic venues and infrastructure. They also reported the progress towards the targets set up in 2007 by the Olympic Delivery Authority (ODA) in the Sustainable Development Strategy. When available, the data used in this project for the construction phase and the Games period was based on the ODA reports and publications.

In order to determine the impacts of different site designs and operation of the buildings in the post-event legacy phase, 3 design scenarios have been developed in this project. The first scenario – 'Business as Usual'– is based on the plans of the London Legacy Development Corporation (LLDC) published soon after the end of the Olympics. The LLCD proposals are based on the redevelopment of the Olympic Park into a typical London mixed area with plenty of green open space and 5 permanent Olympic venues in operation. The other two scenarios – 'Commercial World' and 'High rise, high density' were developed based on the assumptions that they can be feasible alternatives in the post-event period because of the proximity of the site to Central London and the City of London and because of the major public transport links. The choice of post-event site design scenarios is a very complex issue which depends on numerous factors such as the geographical location of the event site, transport links, private-public investment schemes, economic and political situation of the host city and many other aspects. In this project the scenarios were developed based on the current and recent urban infrastructure projects addressing the high-rise developments similar to Canary Wharf, increase of commercial and office space such as construction of numerous commercial offices in the City of London and significant investments in the public transport infrastructure such as the Crossrail project. In this work the number of scenarios is limited to three; however, in reality the number of potential scenarios may be more and will be determined by the majority of key stakeholders during the planning process.

The outlines of all three scenarios are provided in section 4.4.1. The detailed assumptions for each scenario are provided in Appendix 2.

4.4.1 Legacy scenarios analysed in the project.

4.4.1.1 'Business as Usual' scenario - BAU.

The 'Business as Usual' scenario is based on the current proposal by the London Legacy Development Corporation (LLDC, 2012), which builds on the typical London mixed residential/commercial area with 2-3 storeys houses and 4-5 storeys apartment blocks. The future area will include a site consisting of 5 new neighbourhoods with approximately 11,000 new homes (including the Athletes Village) alongside with education, health and community facilities. The Park will have 11 schools and nurseries, 5 Olympic sports venues, 3 health centres, a number of restaurants and shops. The Park will also provide a great business opportunity with 62,000 m^2 of flexible commercial space in the Broadcast Centre and 29,000 m^2 of flexible office space in the Press Centre and close connection to the City of London and Canary Wharf (LLDC, 2012).

4.4.1.2. 'Commercial World' scenario - CW.

The 'Commercial World' scenario is based on the assumption that only a few new residential blocks will be built in the Park comprising of 1,000 apartments. The rest of the area will be a mixture of different types of commercial offices and small industrial units. It is estimated that the total floor area of all commercial buildings will be approximately 3,000,000 m^2 (Appendix 2). The site will also have 5 operating Olympic sports venues, 3 schools and nurseries, a health centre, a number of various size restaurants and retail units. Great transport links and proximity to the City and Canary Wharf business area could potentially make the Park a new commercial hub in the heart of East London.

4.4.1.3. 'High rise, high density' scenario - HRHD.

The 'High rise, high density' scenario is based on the assumption that the Park will comprise a mixture of 20- and 30-storeys residential and commercial buildings. The total floor area of all residential buildings is estimated to be approximately 900,000 m^2; the total floor area of all commercial buildings is approximately 2,100,000 m^2 (Appendix 2). The Park will also have numerous community facilities and social infrastructure, hotels, restaurants, supermarkets and retail units. With more people moving to cities each year, there is a need to utilise land to its maximum potential. Thus, new high rise developments present an opportunity to accommodate more people in those areas where there is a shortage of land.

4.5. Summary.

A proposed novel methodology for sustainability assessment of mega-event projects has been presented in this chapter. Unlike previous proposed methodologies examined in Chapter 3, this framework includes evaluation not only of the impacts from the construction and event phases but also of the impacts resulting from the legacy phase. A mega-event project is a complex system which is comprised of three main sub-systems according to the project's phases: construction, event and legacy. Each subsystem consists of multiple sub-projects of various scale and duration. The system requires some inputs such as materials and energy and produces outcomes which can be positive such as employment and infrastructure, or negative such as environmental burdens. The holistic assessment of the whole system requires consideration of the interactions between the subsystems and trade-offs between economic, environmental and social aspects.

Although all three pillars of sustainability have to be addressed for a holistic evaluation, the objective of this project is the environmental and social assessment of mega-event projects with a special emphasis on the legacy phase. Legacy is by far the longest phase and this is where the long-term impacts will occur and the success of the overall project will be measured. In this project, the duration of legacy is assumed to be 25 years. A series of the optimisation models developed in this work are used to determine the total emissions from the transportation, energy and materials supply of the proposed scenarios. Environmental burdens resulting from MSW treatment are determined using the LCA technique. The models in this work do not take into account the technological progress due to multiple uncertainties associated with the long-term technological development and implementation.

As described in the methodology, mega-event project planning should be carried out in constant consultations with all groups of stakeholders throughout the whole project life cycle. In order to determine the views of stakeholders on particular aspects, a series of surveys is normally carried out. These surveys, however, are typically qualitative and do not allow easy comparison of the stakeholders' views. Chapter 5 provides an example of how the survey results can be quantified using the MCDA tool. Although a survey developed in this work is not directly related to the project's case study, it demonstrates the importance of the inclusion of all stakeholders in the planning process because of their diverse and sometimes conflicting interests.

Chapter 5. Social assessment of mega-event projects and stakeholders' engagement in the planning process.

This chapter addresses social impacts of mega-event projects. First, the chapter provides a summary of the recent studies dedicated to the social assessment of mega-events. Next, an overview of the stakeholders' groups affected by the mega-event projects is provided and the importance of the stakeholders' participation in the planning process is explained. The following section explains how Multi-Criteria Decision Analysis (MCDA) can be applied by decision-makers to quantify social indicators. The next section describes a survey developed in this work. Finally, the results are presented in a graphical way which can assist decision makers to determine and compare the views of various stakeholder groups.

5.1. Social aspects of mega-event projects.

In the past, the main decision-making approach for the evaluation of mega-projects, including mega-events, focused mainly on an extensive economic assessment or a cost-benefit analysis. Recently, however, a decision-making process has shifted towards a triple bottom line approach where environmental and social aspects are also included in the strategic impact assessment. The aim of any assessment is to identify and evaluate all major aspects associated with a proposed mega-project that can potentially negatively or positively impact stakeholders directly or indirectly affected by the project.

Social sustainability is currently widely recognised as important and the concept is increasingly used by the governments, public agencies, policy makers, NGOs and corporations to frame decisions about urban and industrial development on the principles of sustainable development. Although the concept is now extensively applied, there is no a single definition of a social sustainability. Moreover, many definitions of social sustainability found in literature are often conflicting and include a wide range of political, philosophical and practical aspects. For example, Sachs (1999) and Agyeman (2008) argue that the main features of social sustainability are equality, democracy and social justice. Vallance et al. (2011) emphasise the importance of basic needs, creation of social capital and the promotion of stronger environmental ethics. Yang et al. (2014) highlight the importance of community development and energy security. Other authors accentuate the preservation of social values, cultural traditions, well-being and quality of life (Barbier, 1987; Koning, 2002).

Social sustainability assessment is still an emerging field of the urban planning and it is not clearly defined in policy or practice (Woodcraft, 2012). Thus, social sustainability assessment is not a straightforward task. Social indicators are often qualitative and sometimes cannot be precisely defined, quantified or related to a specific benchmark. Social indicators are also subjective; they are not consistent across the community and depend on the viewpoint of various interest groups involved in a planning process: one group may consider some social aspects being positive while the other group might foresee them as negative (Hacking and Guthrie, 2008). Additionally, the long-term nature of mega-event projects inevitably creates many uncertainties, particularly in regards to planning of a legacy phase which normally begins at least 10 years after the submission of the original bid for hosting the event. People's opinions may change over time; thus, their views on the significance of certain issues may also change.

Social assessment of mega-event projects is even more difficult task because of the multiple phases of the project with different sets of social factors to be addressed at each phase. At the first stage –construction of the event site – a typical set of social indicators applicable to major infrastructure projects is normally used. Commonly, the main social indicator set for an infrastructure project includes the following aspects:

- Health and safety of workers, e.g. incident rate, safety performance, lighting conditions, etc.;
- Impact on nearby residents, e.g. increased traffic, air and noise quality, etc.;
- Employment opportunities, e.g. number of jobs created, provision of training, equal opportunities at work, etc.;

- Compliance with building standards and regulations;
- Cultural and heritage conservation;
- Biodiversity and land use.

A set of social indicators for the actual event phase will be different. It will normally address more qualitative aspects regarding the site and sporting events, for example visitors' satisfaction with staging of sporting events and opening/closing ceremonies, venues' design and their visual impact, accessibility and availability of different amenities on site, etc. Generally, a social indicator set for the event phase may include the following:

- Health and safety of athletes and visitors, e.g. air and water quality, security and safety on-site;
- Employment opportunities, e.g. number of jobs created, number of volunteers involved, number of women at work, number of employees who reside in the nearby boroughs;
- Impact on local residents, e.g. increased traffic, noise;
- Easy access to venues and other facilities on site, e.g. proximity to the public transport, provision of facilities for disabled, provision of basic medical facilities on site, availability of restaurants;
- Aesthetic and functionality qualities of the venues and other facilities, e.g. visitors' satisfaction with design of the site and venues;
- Visitors' satisfaction with staging of the event, e.g. organisation of sporting events and ceremonies.

The post-event phase will require another set of social indicators, which will combine two different sets:

1. A first social indicator set requiring a typical set for the evaluation of infrastructure projects and which will be applied during the demolition of the temporary event facilities and while the construction of new residential/commercial buildings takes place.

2. A second indicator set for the post-event phase will comprise the indicators necessary for the assessment of urban communities. This set has to be developed at the early phase of the planning process in order to identify those social aspects that will have the highest impacts and incorporate them in the scenario development.

Despite being widely accepted as one of the main pillars of sustainability, the literature that focuses specifically on the social sustainability of urban communities is still rather limited (Dempsey et al., 2011). Moreover, there is no general agreement amongst researchers on the criteria that should be used in the social sustainability practice (Sharifi and Murayama, 2013). Table 5.1 provides a list of criteria used by some researchers in their recent studies on social sustainability.

Table 5.1. Criteria for social sustainability of urban communities.

Criteria considered	Reference
Citizen participation, social interaction, feeling of belonging, collective action, mutual support, safety, access to facilities and amenities, relationships between neighbours	Choguill, 2008
Social equity, access to facilities and amenities, affordable housing, social interaction, safety/security, satisfaction with home, participation in collective group/civic activities	Bramely et al., 2009
Social justice, social/community well-being, engaged governance, social infrastructure, community development, human and social capital	Cuthill, 2010
Access to facilities and amenities, amount of living space, community spirit and social interaction, safety, satisfaction with the neighbourhood	Dave, 2011
Social interactions, participation, community stability, social equity, safety and security, sense of place	Dempsey et al., 2011
Accessibility, social capital and network, health and well-being, social cohesion and inclusion, safety and security, local democracy, participation and empowerment, cultural heritage,	Weingaertner and Moberg, 2011

education and training, equal opportunities, housing and community stability, social justice, sense of place, attractive public realm	

Urban community indicators cannot be evaluated before the community actually exists. However, it is possible to identify which indicators are considered to be the most significant by existing communities and incorporate the findings into the decision making process of the proposed future urban design scenarios. Thus, planning of mega-event projects should not be concentrated solely on the event itself but has to incorporate also all the phases of the project with a particular emphasis on the legacy.

It is argued (AgenZ, 2013) that both social and economic outcomes of many past mega-events have been neutral and often negative due to the lack of an early holistic planning process and a sustainability impact assessment of the overall project. This highlights the need to shift the emphasis from the sole evaluation of the staging of the event itself to a broader objective which focuses also on the post event phase as this is where the long-term benefits will occur. Hence, mega-event planning must be embedded in the long-term city development plant, necessary for the coordination of a large number of actors involved in the organisation of the event and the subsequent post-event site redevelopment (AnenZ, 2013).

5.2. Stakeholders' engagement in the planning process of mega-event projects.

Planning of design scenarios for the event and post-event site and, in particular, the evaluation of social benefits and drawbacks of a mega-event project is strongly influenced by the numerous stakeholders and interest groups involved.

Mega-event projects normally attract a lot of public and media attention as they involve major regeneration and infrastructure development schemes that may require relocation of residents living nearby the event site, hence affecting communities and changing people's lifestyles. Therefore, it is argued that planning should include inputs from different community groups to promote public debate and community involvement (Cursoy, 2006).

Construction of the event venues and transport infrastructure will inevitably entail certain negative impacts, for example, noise and air pollution and increased traffic due to deliveries of building materials to the site and removal of construction waste. Similar impacts, perhaps on a smaller scale, will occur after the event is over, when the site is being redeveloped and integrated with the adjacent city areas. These and many other factors may lead to public hostility towards event planners and local authorities. It is argued that in order to avoid potential conflicts, it is necessary to abandon traditional political planning approaches and adopt a more democratic planning model allowing public participation in the discussions on the expected costs and potential social benefits throughout the decision process (Cursoy, 2006).

The development of an assessment methodology is a complex task and decisions are often uncertain, with multiple stakeholders often holding conflicting perspectives about problems and solutions (Jones et al., 2005). Figure 5.1 summarises the main groups of actors involved in a decision-making and planning process of a mega-event project.

In recent years, the central importance of stakeholders' participation in a social impact assessment has been widely recognised and discussed in the literature (Morrissey et al., 2012). Sheate et al. (2001) and Sheate and Partidário (2010) discuss the need for involvement of a wide range of actors, including project stakeholders, policy makers and the wider public to enable long-term and broad-spectrum decision-making. It has been recognised that a participatory process of social impact assessment can be a way to mitigate conflict and enable inclusion of all interest groups (Peltonen and Sairinen, 2010).

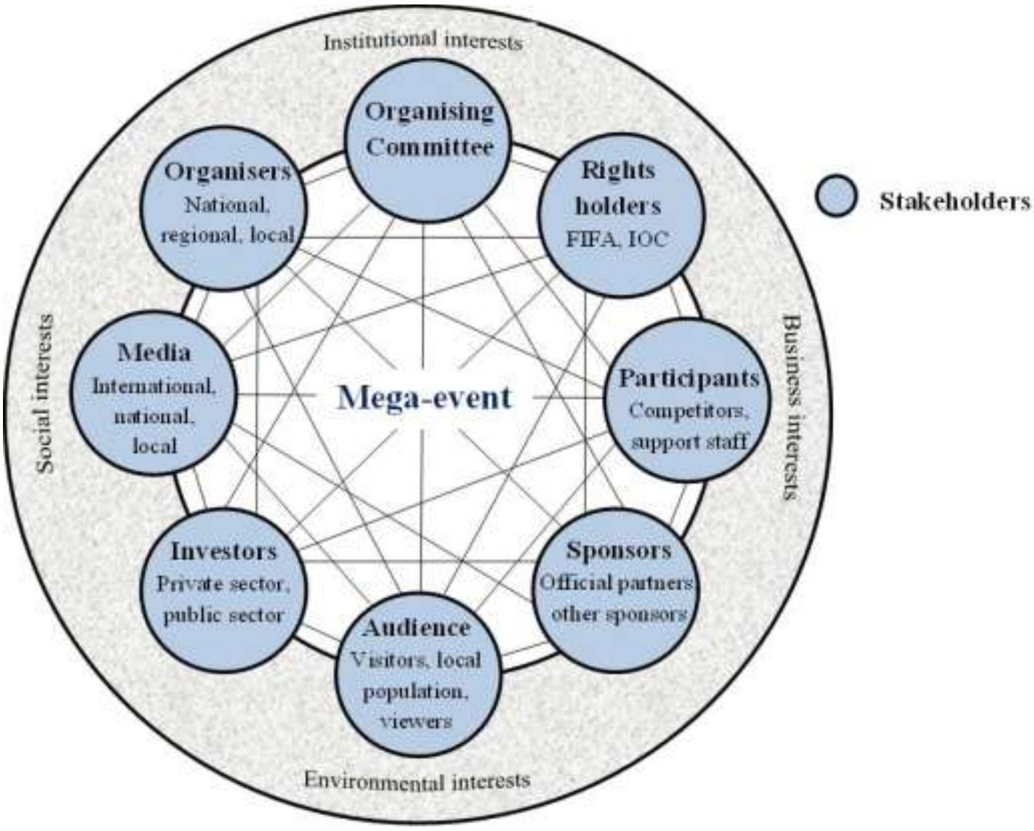


Figure 5. 1. Stakeholder groups involved in a mega-event project (adapted from AgenZ, 2013).

A community often concentrates on the short-term negative impacts associated with construction of the event infrastructure without recognising the long-term social and economic benefits that will arise from new transport and built infrastructure facilities that will be made available and used long after the event is over. They also might not be able to envisage the long-term advantages of reintegrating the former event site into the city as a new residential/commercial area, which entails the creation of increased number of residential dwellings, number of jobs created, new public amenities and green open spaces. Hence, open discussions of the costs and benefits of the proposed design scenarios between different stakeholders are key to a better understanding of the overall long-lasting impacts of mega-event projects by various community groups. It is noted that a participatory approach will enhance dialogue between stakeholders and, potentially, enabling broader support for the implementation of the proposed actions (Carter et al., 2009). A mega-event site occupies a large area of land; it is argued that a key goal of long-term planning is to ensure the final development and use of the land is in the general 'public interest' and all views are taken into account (Miller and Buys, 2012).

5.3. Assessment of qualitative social indicators using MCDA.

Public participation in the planning of mega-event projects may take different forms. It can be in the form of public hearings and discussions, workshops, advisory committees, etc. Various types of surveys are usually distributed at such meetings in order to obtain viewpoints of different stakeholder groups on social implications of the proposed development. Normally, survey questions are developed by planners who want to find out stakeholders' views on various social aspects that have to be addressed while planning the future scenarios. The surveys are then analysed in order to identify which social factors are considered to be the most important by the majority of stakeholders and, therefore, should receive priority in allocation of resources.

One of the techniques that are widely used for the evaluation of qualitative social indicators is multi-criteria decision analysis (MCDA) (Cinelli et al., 2014; Santoyo-Castelazo and Azapagic, 2014; Garmendia and Gamboa, 2012; Munda, 2006). It is aimed at supporting decision-makers who are faced with numerous and conflicting choices (Lootsma, 1999). MCDA is used to quantify various qualitative social indicators by assigning different numerical values according to the views of stakeholders participating in the assessment process. There are different MCDA approaches as summarised in section 2.8.1. These approaches share common mathematical elements, i.e. values for alternatives are assigned for a number of dimensions, then multiplied by weights and finally combined to produce a total score (Huang et al., 2011).

Planning of mega-event projects normally involves numerous stakeholder meetings and workshops and multiple surveys will be developed and analysed concerning different social aspects of the proposed scenarios. MCDA can be a valuable tool to examine the outcomes of stakeholders' surveys and produce quantitative results that can assist in the subsequent steps of the decision making and planning process.

5.4. Stakeholders' social survey developed for the current study.

A survey of social indicators has been developed for the current project in order to investigate how MCDA can assist with decision making when a number of various stakeholder groups are involved in planning. Such a survey can be used at the early stages of the decision making process prior to designing the event site and planning for the post-event site redevelopment. Its aim is to identify the most significant social aspects from the point of view of various stakeholder groups that have to be addressed and incorporated into the site design.

A set of questions in the survey was developed in consultation with social scientist and urban planners from the UCL Development Planning Unit (DPU) in order to identify how different features of the post-event site design scenario are viewed by different sets of stakeholders. A survey for the current study consists of 10 questions which address a number of social aspects of the post-event site design mainly regarding the building and transport infrastructure and green open space. In reality, the survey will consist of more questions and address other different aspects, e.g. safety and security.

The questions of the survey for this project are:

1. How important is the amount of green open space in the new developed post-event Olympic Park?
2. Is it important for you that the green open space has multiple easy accesses instead of only one entrance?
3. How important is for you to have an easy access to/from the Park to the public transport network (rail, underground, buses)?
4. Is it important for you if the Park has a large cycling network?
5. How important is for you to have electric vehicles infrastructure?
6. How important is for you to have easy access to basic medical facilities?
7. How important is for you to have a large number of sporting events held annually in the post-event Olympic sports venues?

8. How important is for you the availability of different amenities in the Park (restaurants, shops, galleries)?
9. How important is for you the availability of children's facilities (playgrounds, schools, nurseries)?
10. How important is for you the 'Prestige factor' of the Park? In your opinion, does the fact that the site is the legacy of the London 2012 Olympic Games make it more prestigious area than other parts of London?

The survey was distributed to a number of students and academic staff at UCL. The total number of surveys collected and analysed was 100 (comprising 5 stakeholder groups with 20 participants in each group). Each participant was assigned to one of the 5 stakeholders' groups and was asked to think of himself/herself as a member of that particular stakeholder group. First, participants were asked to give a score from 1 to 10 to each of the questions listed above, where 10 was deemed the most important score and 1 the least important score. Any value between 1 and 10 could be applied to each question. Next, the participants were asked to give a weight to each indicator, again a number between 1 and 10. In this case, only one specific number could be allocated to each question, so that the most important question had a score of 10, the next important had a score of 10 and the least important had a score of 1.

The participants were allocated to one of the 5 stakeholder groups. During the consultation with social scientists and urban planners it was identified that the following stakeholder groups will account for the majority of the key stakeholders:

A. Potential resident of the Olympic Park (considering purchasing a flat/house in the Park in the near future).
B. Potential employee in the Olympic Park (assume you work in the office located in the Park and you live in another part of London).
C. Potential visitor to the Park (you live in London and thinking of visiting the Park in the future).

D. Potential investor (considering renting/buying a commercial property in the Park to move your existing business there or open a new business or investing in the residential development).
E. Local authority of the nearby boroughs (want to improve social performance of the borough and community development).

The responses to the questionnaire were analysed and the overall results for all groups of stakeholders were produced. The outcomes of such a survey can help decision makers to identify the most important social factors that have to be taken into account and incorporated into the design plans of the event and post-event sites. At the later stages of a mega-event project, additional surveys should be developed and distributed amongst the stakeholders. The further questions should address other numerous criteria applicable for broader, more extensive evaluation of the proposed event and legacy design scenarios. The questions may address locations and designs of specific buildings such as community or medical centres, positions and sizes of parking lots and bus stops, design and size of residential dwelling, etc.

In practice, planning normally involves more stakeholder groups and surveys may comprise more questions. However, it is argued that if the surveys are too long it might lead to poor quality of responses (Barfod et al., 2011), and engagement of a large number of stakeholders may be very time consuming while analysing and summarising MCDA results (Jeswani et al., 2010).

5.5. Analysis of the survey responses and MCDA results.

The purpose of MCDA was to calculate the scores attributed to the social aspects addressed in the survey in order to determine which ones are regarded as the most significant by the majority of participants.

Figures 5.2 - 5.6 illustrate the averaged weighted scores of the social indicators addressed in the survey for each stakeholder group; figure 5.7 shows the overall average score for all groups.

Figure 5.2 presents the MCDA results for the stakeholders' Group A representing 'potential residents in the post-event Olympic Park'. It can be seen that the highest weighted score was assigned to 'Easy access to public transport' (66) followed by 'Availability of different amenities' (54) and 'Access to medical facilities' (53). The lowest weighted score was allocated to 'Electric vehicles infrastructure' (15). It can be seen that social factors associated with the legacy of the London 2012 Olympic Games received lower weighted scores than other factors: an overall score of 24 was given to the 'Prestige factor' and 27 was assigned to the 'Sporting events'.

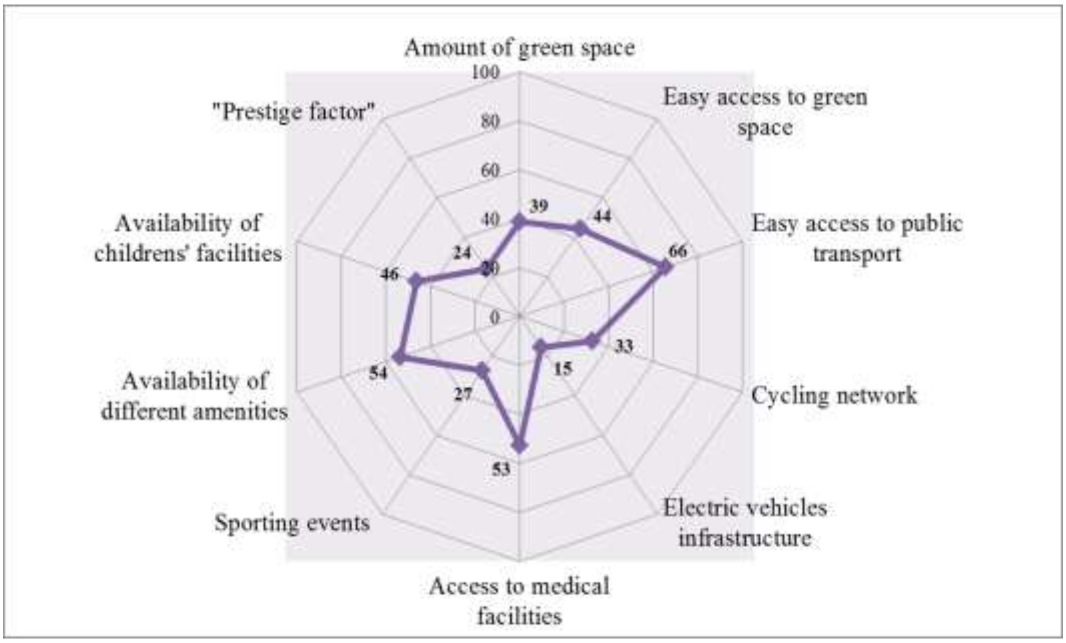


Figure 5. 2. Group A – Potential residents in the Queen Elizabeth Olympic Park.

Figure 5.3 provides the MCDA results for the stakeholders' Group B representing 'potential employees in the post-event Olympic Park'. It can be seen that Group B assigned the highest weighted scores to the same three categories as did Group A. However, it is clear that Group B perceived 'Easy access to public transport' (score of 87) as far more important than the 'Availability of children's facilities' (score of 16), 'Electric vehicles infrastructure' (score of 18) and 'Prestige factor' (score of 25).

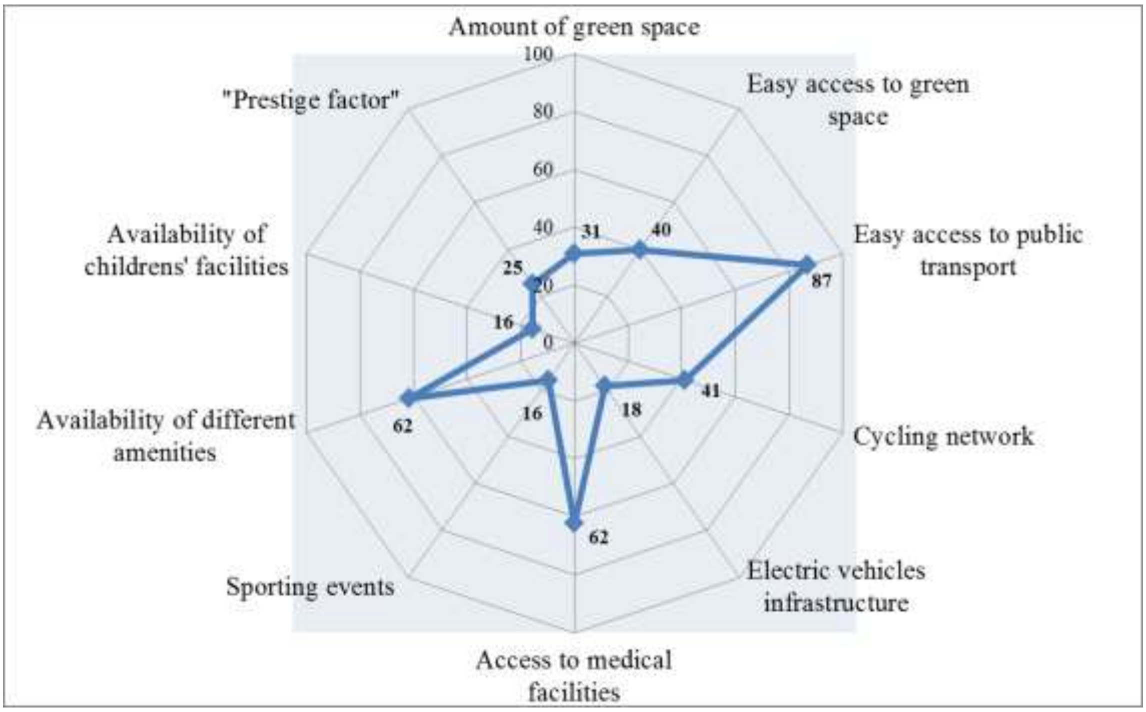


Figure 5. 3. Group B – Potential employees in the Queen Elizabeth Olympic Park.

Figure 5.4 shows the results for the stakeholders' Group C representing 'potential visitors to the post-event Olympic Park'. In this case, the main priority is given to having 'Easy access to public transport' which obtained the highest score of 76. The 'Amount of green space' and 'Easy access to green space' also deemed important by this group of stakeholders, with scores of 55 and 53 respectively. The lowest score is assigned to 'Electric vehicle infrastructure' (13) followed by 'Prestige factor' (17).

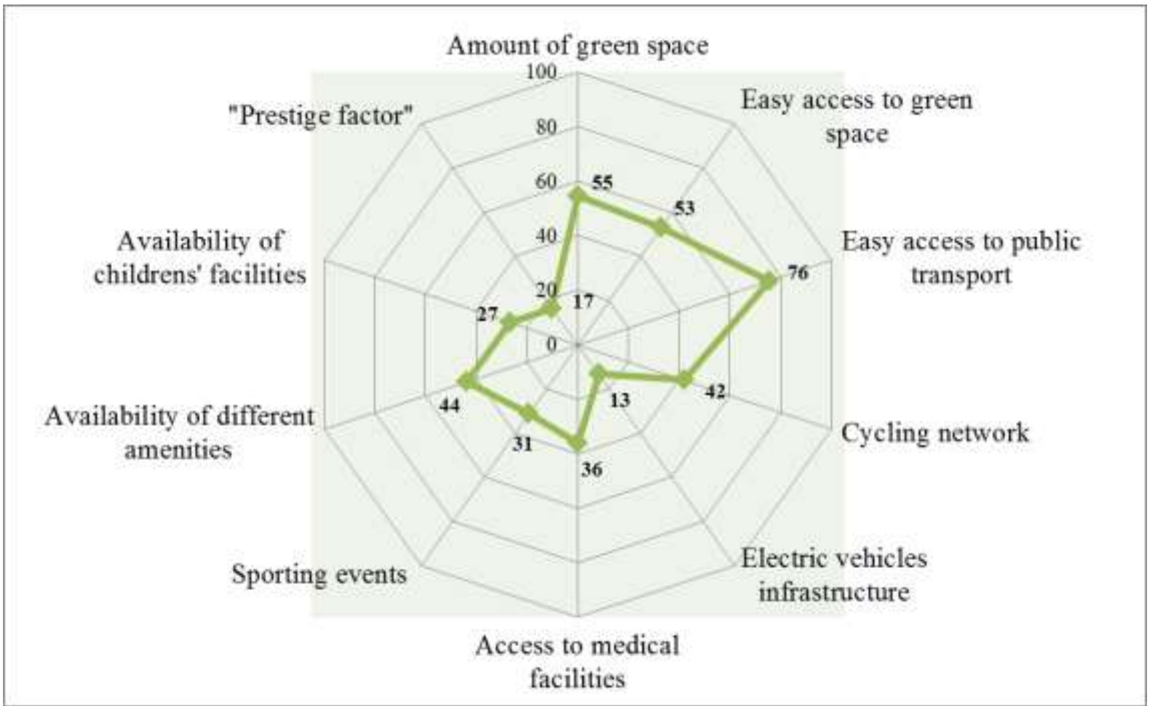


Figure 5. 4. Group C - Potential visitors to the Queen Elizabeth Olympic Park.

The MCDA results of the stakeholder Group D representing 'potential investors in the post-event Park' are illustrated in figure 5.5. The highest score of 81 is assigned to 'Easy access to public transport'. The second most important indicator considered is the 'Availability of different amenities' followed by the 'Prestige factor', with scores of 58 and 55 respectively. 'Electric vehicles infrastructure' received the lowest score of 17 followed by 'Availability of children's facilities' with a score of 27. This group of stakeholders gives similar priorities to 'Availability of green open space' and 'Availability of medical facilities' assigning a score of 31 to both categories. 'Cycling network' and 'Sporting events' categories are regarded as slightly more important by the investors' group with the scores of 32 and 34 assigned respectively.

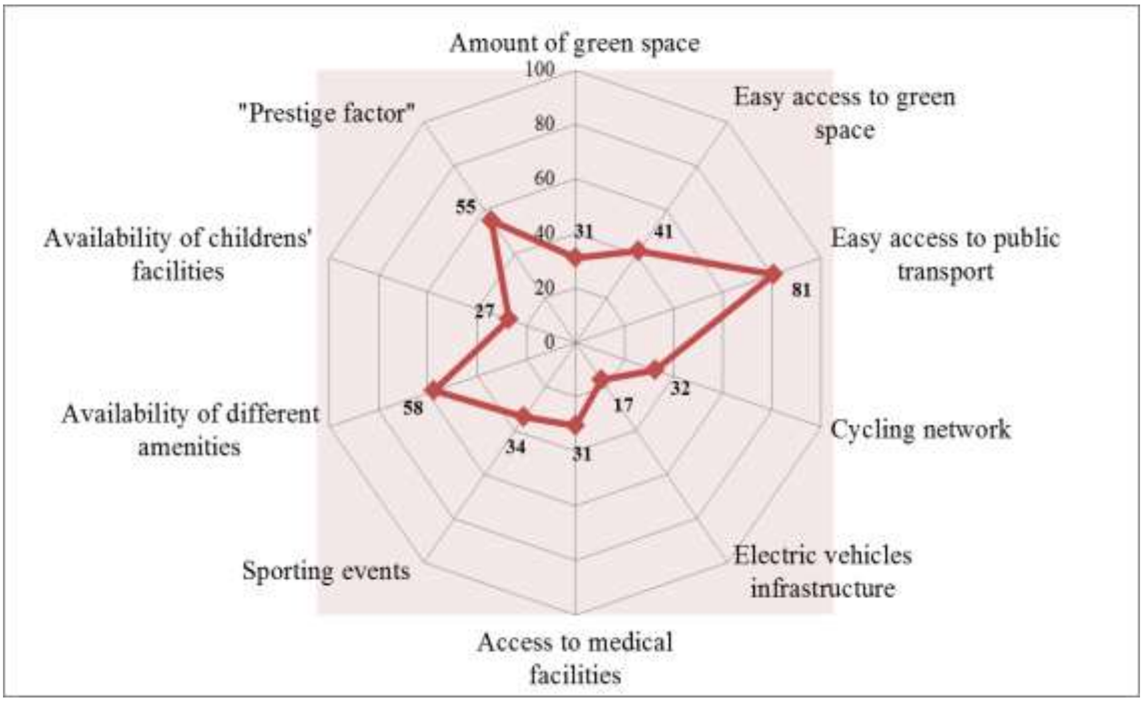


Figure 5. 5. Group D – Potential investor/employer in the Queen Elizabeth Olympic Park.

The outcomes of stakeholder Group E representing 'local authorities' are shown in figure 5.6. They assign the highest weighted scores to 'Easy access to public transport' (71), 'Availability of different amenities' (60) and 'Availability of children's facilities' (55), whereas 'Electric vehicles infrastructure' has received the lowest score of 14. The scores for indicators 'Easy access to green space', 'Access to medical facilities' and 'Sporting events' were almost equal. However, this stakeholder group regarded the 'Prestige factor' more important than groups A, B and C giving it the overall score of 33.

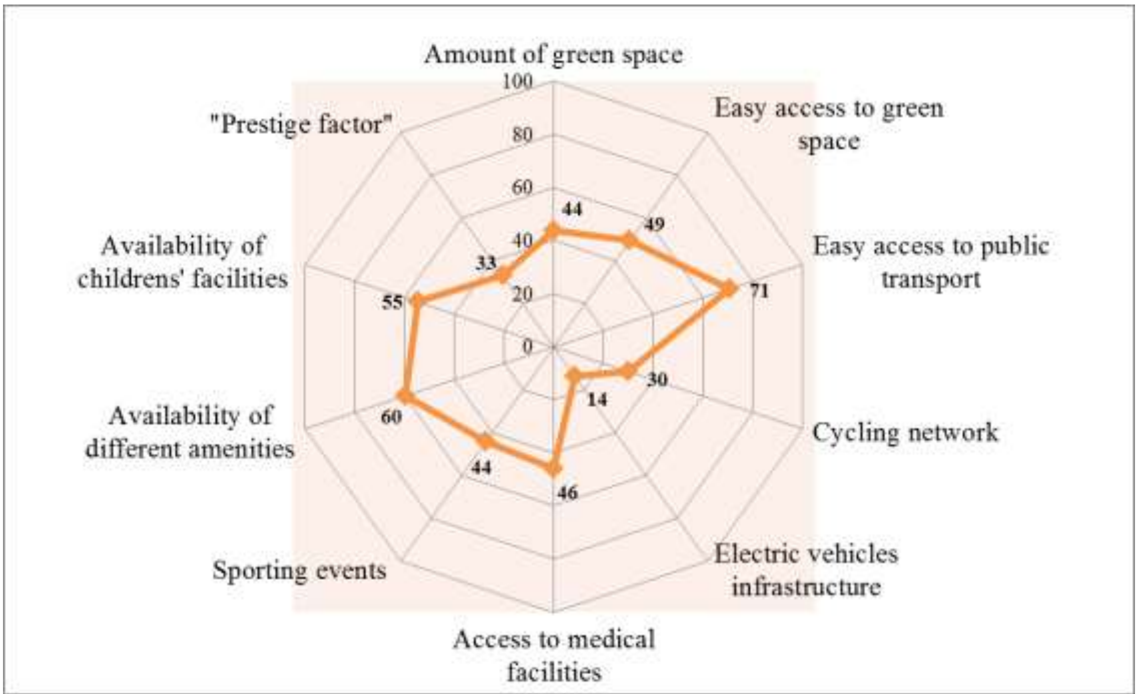


Figure 5. 6. Group E – local authorities of the Queen Elizabeth Olympic Park.

Finally, figure 5.7 provides the average weighing score for all stakeholder groups. Perhaps as expected, the highest score of 76 is assigned to ‘Easy access to public transport’, which is considered the most significant aspect by all stakeholder groups. ‘Availability of different amenities’ is considered to be the next important factor with an overall score of 55, followed by ‘Easy access to green space’ and ‘Availability of medical facilities’ with an identical score of 45. It has to be noted that the accessibility of the open space is regarded more important by the stakeholders than the actual amount of green area available.

‘Electric vehicles infrastructure’ is considered the least important indicator by all stakeholder groups; therefore, it also has the lowest overall average score. ‘Sporting events’ and ‘Prestige factor’ both received the overall average score of 30 which means that the majority of all groups of stakeholders do not differentiate the site from other parts of a city on the basis of its connection to the past Olympic Games. The only group which gave a relevantly high score to ‘Prestige factor’ was a group representing potential investors, as expected.

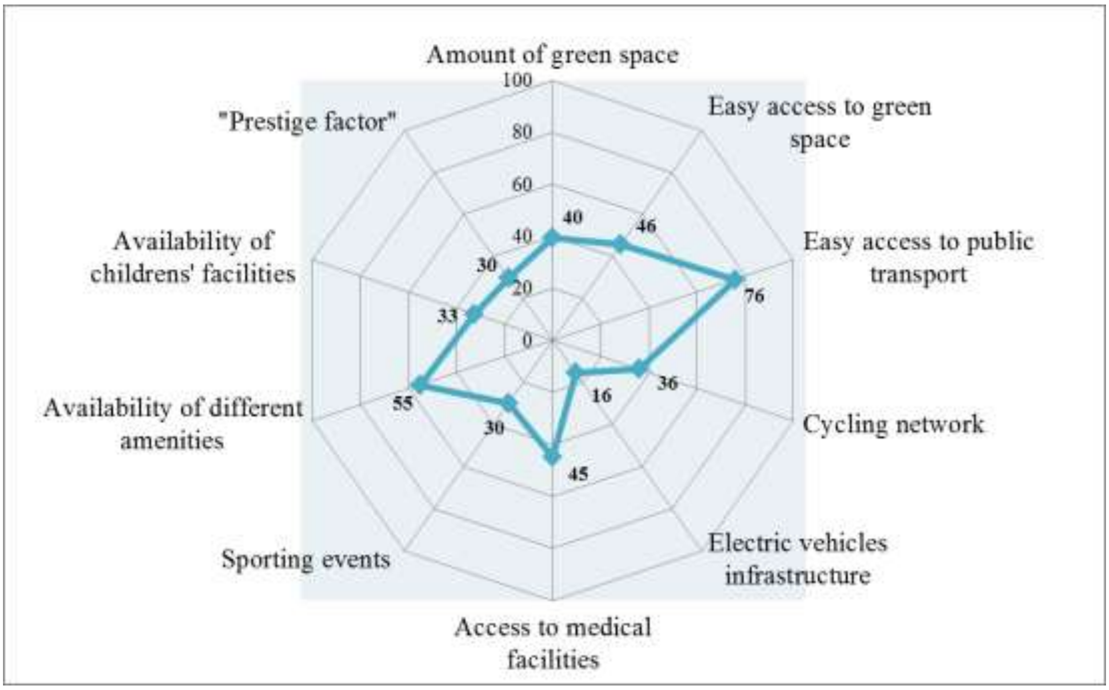


Figure 5. 7. Overall average weighing score for all stakeholder groups.

It is clear that MCDA can be a valuable tool to compare those alternatives that cannot be easily accessed using other evaluation tools, particularly when a number of various actors are involved in the assessment process. The main advantage of the MCDA is that it can combine quantitative and qualitative, monetary and non-monetary indicators. Hence, it can also be used for integrated assessment of economic, environmental and social indicators when different groups of stakeholders are involved in decision making.

5.6. Summary.

Social sustainability has recently been widely incorporated in the urban planning and practice; however, it is still an emerging field and there are no clearly defined standards on how to carry out social sustainability assessment, which indicators to include in the assessment and which evaluation tools and techniques to use.

Social assessment of ‘mega-event’ projects is a particularly complex task due to the long-term nature of the project, multiple phases that require specific indicator sets and a large number of different actors involved. It has been identified that participation of all stakeholder groups affected by the project is crucially important. All groups of stakeholders should be involved in the planning process from the early phases of the ‘mega-event’ project planning so that the most significant social aspects are identified and incorporated in the design of the event site early on. Moreover, long-term planning for the post-event legacy phase should also start at this stage and the design for both event and post-event sites should be carried out concurrently. A post-event site will eventually become an urban area; therefore, it should be embedded in the long-term city development plan from the start of the project.

The engagement of different stakeholder groups in the planning process normally involves surveys. In this chapter it was demonstrated how social aspects can be evaluated through the distribution of surveys to various groups of actors and how the MCDA technique can be used to analyse the answers and present surveys’ results in quantitative terms. The survey results illustrated how MCDA is applied in the planning process of urban mega-projects to identify the most significant social aspects according to the majority of stakeholders and incorporate them into the future design scenarios. Although social aspects are mainly qualitative, the MCDA allows quantifying them by applying weighted scores by the survey participants.

The survey results demonstrated that different stakeholders perceive and prioritise social aspects differently. The results also show the importance of choosing carefully the sample of stakeholders required to undertake the test to make sure that a broad range of interested parties of different ages, gender, interests and backgrounds is equally represented in the survey.

In this project, a survey was trialled at UCL. The majority of the audience was made of young students who clearly did not perceive the importance of aspects such as the 'Availability of children's facilities' and 'Amount of green space' as their imminent priority. Hence, this exercise shows also the limitations of the approach if the questionnaire is distributed only to a specific group of stakeholders. In this case, the results do not reflect the breadth of the views of all actors which may lead to potential conflicts of interests and delays in the planning process in the future.

The experimental survey described in this chapter does not cover the full range of social sustainability aspects because the main objective of the work was to determine the applicability of the proposed methodology and not to carry out a complete social impact assessment. In practice, such surveys include more questions addressing other social aspects. Multiple public workshops, meetings and stakeholder consultations are unavoidable in the planning of mega-event projects due to the complexity and the scope of such projects and several surveys will be distributed and analysed before the final decision is agreed on by the majority of stakeholders.

Social assessment of mega-event projects remains a complex task mainly due to a number of actors involved in the planning process and, therefore, subjective views of different stakeholders. Further work requires participation of social scientists to identify all important social aspects to be included in the surveys, fully develop comprehensive questionnaires and determine the best ways of conducting stakeholder meetings and consultations in order to develop a holistic sustainability assessment methodology where social, economic and environmental impacts are equally addressed and evaluated.

Chapter 6. Evaluation and optimisation of the environmental impacts.

This chapter provides the first part of the environmental assessment presented in Chapter 4. It is dedicated to the evaluation and optimisation of the environmental impacts resulting from the transportation of visitors and materials, use of energy and water, and removal of wastewater during all phases of a mega-event project. It begins with a summary of the recent publications on the use of different optimisation methods as a tool for sustainable infrastructure systems planning. Next, a series of the optimisation models developed in this work are presented followed by the results. The final part summarises the overall results, analyses the main findings and explains how the results can be used by the decision makers during the planning of mega-event projects.

6.1. Development and application of optimisation models in recent practice.

In the last few decades significant progress has been made in mathematical programming techniques including advanced system optimisation methods. The development of commercial modelling systems that can facilitate the formulation of optimisation problems such as AIMMS, AMPL, GAMS and OPL has led to great advances in solving very large problems with relatively small effort. All modelling systems allow the user to implement models in the form of algebraic models involving variables, constraints and objective function. Due to the ability of using indexed variables, the models can be easily implemented in compact forms, similar to those expressed analytically. Furthermore, a major advantage of these modelling systems is that they automatically interface with optimisation solvers with which the user need not to be concerned. Finally, the modelling systems are capable of interfacing with databases and spreadsheets, which allows easy data exchange (Grossmann, 2012).

System optimisation is now widely used in chemical and process engineering, building design, product design and manufacturing, supply chain and operations management, energy, water and waste systems modelling and many other fields. This section provides a short overview of selected publications on the optimisation algorithms which were applied as a planning tool for the sustainable infrastructure systems.

Optimisation algorithms solve problems with only one objective function, which is often to maximise profit or minimise costs. For example, Corsano et al. (2011) presented a mixed integer non-linear programming (MINLP) model for the simultaneous optimisation of supply chain and plant design for ethanol production from sugar cane with the objective to maximise the net profit. The results presented the evaluation of different scenarios considering fluctuations in cost, demands, raw materials supply and other factors.

Multi-objective optimisation methods address two or more objectives by exploring trade-offs between competing objective functions. Most commonly, multi-objective optimisation models address the economic and environmental outcomes of a particular process or system. For example, Hugo et al. (2005) presented an MILP multi-objective model developed for strategic investment decision making in regard to the future hydrogen infrastructure. One of the objective functions was to minimise the net present value while the other one was to minimise the GHG emissions. The key features addressed in the model were the optimal selection of the primary energy feedstocks, allocation of conversion technologies to either central or distributed production sites, design of the distribution technology network and selection of refuelling technologies. The model was applied to a case study and the results were presented as a set of non-inferior trade-off solutions on a Pareto curve.

A large number of optimisation models have recently been developed with the aim of identifying the optimum design for a specific infrastructure system in terms of minimising its environmental impacts and economic costs. Sustainable energy supply is one of the most important current issues; therefore, a lot of models have recently been developed in order to identify optimum energy systems.

Kim et al. (2012) proposed a model, which objective was to minimise the costs of the potential renewable energy system for South Korea with respect to the production cost. The model takes into consideration CO_2 emission rates, CO_2 costs, initial capacities, capacity factors, size limits of various energy generation facilities, capital and fixed costs of different types of conventional and renewable energy sources such as coal, natural gas, nuclear power, wind power, solar and biomass. The results of the study illustrated that biomass and solar energy are essential for satisfying the increasing energy demand in the future. The model was identified as a valuable decision making tool for planning energy systems as the results of the study reflected the real energy situation in Korea and complied with the national renewable energy targets.

Ren et al. (2010) presented a multi-objective optimisation model that was developed to analyse the optimum operating strategy of a distributed energy resource (DER) system. The model combines minimisation of energy costs with the minimisation of environmental impacts represented in terms of CO_2 emissions. The distributed energy systems considered in the study included photovoltaics (PV), fuel cells and gas engine. The results showed that minimisation of economic costs led to the increased CO_2 emissions. It was also identified that the adoption of carbon tax had marginal influence on the operation of the distributed energy system unless the tax has a quite high value.

Optimisation is also widely used in order to identify how to improve the energy performance in buildings. Such studies take into consideration properties and costs of different building materials and are used either to estimate the potential performance of new buildings or how to improve the performance of the existing buildings through various retrofit schemes.

Diakaki et al. (2008) developed a multi-objective optimisation model to investigate the improvement of the energy efficiency in buildings. Application of the optimisation model to a case study of a simple building with decision variables reflecting alternative choices regarding the window type and insulation materials demonstrated feasibility of the approach. However, it was identified that when a larger number of different real-world criteria were applied (such as indoor comfort, environmental and social criteria, etc.), the problem became too complicated in terms of both modelling and finding an optimum solution.

Asadi et al. (2012) developed a multi-objective optimisation methodology of building retrofit strategies. The model includes four types of decision variables in regards to the external walls insulation materials, the roof insulation materials, the window types, and the solar collector type. The objective functions are costs, energy savings and thermal comfort. The model was applied to a case study – a semi-detached house constructed in 1945 and situated in central region of Portugal. The result verified the practicability of the modelling approach and outline potential problems.

Optimisation methods are also often applied when designing sustainable water systems. Lim et al. (2010) presented a non-linear programming (NLP) optimisation model for the integrated urban water cycle system formulated on the basis of the superstructure model. The objective function is to minimise the consumption of the water resources imported from the regions beyond a city boundary. The optimisation model takes into account the maximum water and wastewater flowrates, consumption of the non-renewable ground water and concentration of contaminants. To validate the model, an integrated urban water cycle system was calculated for a case study - Ulsan metropolitan city in Korea. The results showed that restructuring the water network of Ulsan can potentially decrease the average concentrations of pollutants in the influents supplied for drinking water and reduce the overall volume of water resources and electricity consumption by the water infrastructure.

Kurek and Ostfeld (2013) presented a multi-objective methodology for modelling the water distribution systems. The decision variables included pump's speed, storage tank sizes and disinfectant concentrations. One of the objectives was to minimise operation costs, another objective was to improve water quality. The model was solved according to certain constraints such as flows, pressures, continuity, etc. The results were generated as a Pareto set presenting values for the energy and storage costs and aggregated water quality. The results proved the feasibility of the proposed model and its potential for serving as a decision tool.

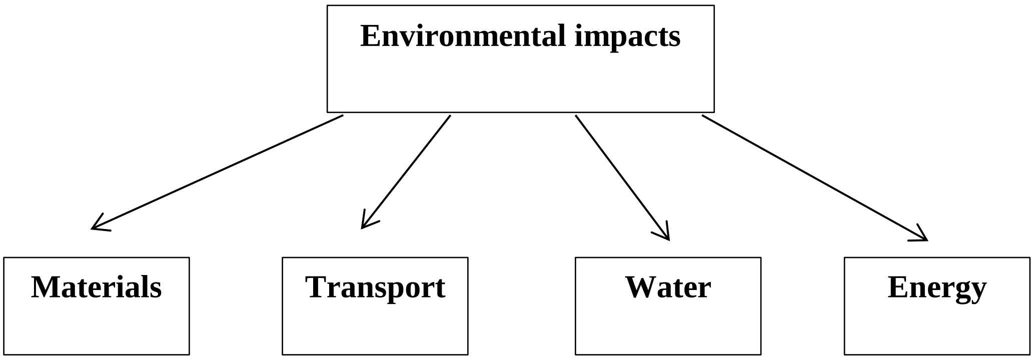
The above studies provide some examples of the application of the optimisation techniques to various infrastructure systems. The type of the optimisation method depends on the objective function and the nature and scope of the problem. In this project a series of the optimisation models were developed with the aim to determine the optimum design scenario for the event and post-event site in terms of minimising environmental impacts resulting from the resources, energy and transport use during all phases of a mega-event project.

6.2. Optimisation of the environmental impacts of a mega-event project.

This chapter provides the description, mathematical formulation and the results of the computational models that were developed as a part of the overall project methodology described in Chapter 4. The main objective of these models is to minimise the environmental impacts of different stages of a mega-project, subject to a number of certain constraints.

First, the models can be used at the design phase to optimise the environmental impacts of the construction of alternative event site design scenarios. The results can also serve as a benchmark for similar future mega-events. Second, the environmental impacts of the actual event can be optimised by identifying those areas that have the highest impacts and exploring the options on how to reduce those impacts. Finally, the environmental burdens of the construction and operation of the post-event site alternative design scenarios can be optimised. Figure 6.1 provides a summary of the environmental impacts accounted for in the models described in this chapter.

The literature review in Chapter 3 provided a summary of several studies which attempted to quantify various impacts of mega-event projects. It was identified that mainly the construction and event stages were taken into account in most of the studies without consideration of a post-event legacy phase. The main objective of this work is to carry out the evaluation and optimisation of the environmental impacts of the whole life cycle of a mega-event project with particular emphasis on the post-event legacy phase.



Construction			
Embodied emissions from construction materials for venues and transport infrastructure construction	Emissions from the transportation of construction materials and waste	Emissions associated with water supply for irrigation during construction	Emissions from energy used during the construction of venues and infrastructure
Event			
	Emissions from the transportation of visitors, athletes, media, officials, employees during the event	Emissions from water and wastewater for the operation of sports venues, Olympic Village, media centres and other building on site. Emissions from water supplied for the irrigation of green spaces.	Emissions from energy used for the operation of sports venues, Olympic Village, media centre and other buildings during the event.
Post-event			
Embodied emissions from construction materials of the post-event site	Emissions from the transportation or residents, employees and general visitors. Emissions from the transportation of visitors for sports events.	Emissions from water and wastewater for the operation of residential and non-residential buildings and sports venues. Emissions from water supplied for the irrigation of green spaces.	Emissions from energy used for the operation of sports venues, residential and non-residential venues.

Figure 6. 1. Environmental impacts of different stages of a mega-event project included in this work.

The optimisation models can be a valuable tool for the decision makers and planners of similar mega-event projects because they can provide information not only about the overall emissions but also about the quantities of the resources and energy used at each stage of the project. This data is crucial because the emissions conversion factors for energy, materials and fuels vary significantly depending on the aspects such as the geographical location of the site, grid electricity mix, or manufacturing processes of different materials. For example, in the UK the emissions conversion factor for supplying 1 litre of water is relatively low because water is not a scarce resource. However, this might not be the case in other countries where water supply and treatment results in much higher emissions value per litre than in the UK and the same quantity of water will have different environmental impacts. Therefore, the models developed in this work can be used to compare the resource usage and emissions between similar events and to establish performance benchmarks for the whole system and numerous sub-systems based on the results for the optimum design scenarios.

6.3. Description of the project phases and the baseline scenarios.

The data provided in this section is presented for the baseline scenarios in which certain variables such as different types of venues, number of buildings, number of residents and employees are determined according to the constraints specifying minimum and maximum values for each variable for each event and post-event site design scenario. In sections 6.4 – 6.6 the emissions will be first evaluated for these baseline scenarios and the sensitivity analysis will be carried out to investigate which variables have the highest impacts on the overall performance of the whole system. Next, constraints will be released where possible in order to determine the optimum scenarios.

6.3.1. Construction and staging of the London 2012 Olympic Games.

One of the main objectives set up in the Sustainable Development Strategy for the London 2012 Olympics was to maximise the use of the existing infrastructure and venues for sport events during the Games (London2012, 2007a). However, the majority of the events and ceremonies usually take place at the new Olympic Park that is built in a host city specifically for this event. For the London Games, the new Olympic Park was built in East London that comprised of new 8 Olympic sports venues, broadcast and media centres, the Olympic Village and other venues. The project also involved the construction of the new transport infrastructure which provided visitors with the easy access to the Park by different types of public transport. The maximum capacity of the sports venues is provided in table 6.1.

Table 6. 1. London Olympic Park venues' capacity (GLA, 2004).

Venue	Capacity (number of spectators)
Olympic Stadium	80,000
Aquatic Centre	17,500
Water Polo Arena	5,000
Basketball Arena	12,000
BMX Circuit	6,000
Handball Arena	7,000
Hockey Centre	15,000
Velodrome	6,000

The data on the quantities of the construction materials of all event venues and transport infrastructure, water and energy used during the construction and staging of the event is provided in Appendix 1. Table 6.2 provides the floor area of the Olympic Village and Broadcast and Media centres that is used for the evaluation and optimisation of the environmental impacts associated with the energy and resource usage in these venues during the Games and in the post-event legacy phase.

Table 6. 2. Estimated total floor area (m^2) of the Olympic Village (considered as residential buildings), Broadcast Centre and Media Centre (considered as office buildings).

Floor area of each type of venues built for the Games period and green open space in the Park (m^2).		Reference
Total internal floor area of all apartments in the Olympic Village (2800 apartments)	196,000	OPLC, 2011
Total internal floor area of the Broadcast Centre	62,234	OPLC, 2011
Total internal floor area of the Media Centre	29,428	OPLC, 2011
Total area of green open space	1,040,000	OPLC, 2011

It was estimated that the number of arena spectators per day in the Olympic Park during the Games was 269,490 and the number of spectators per day during the Paralympic Games was 212,916. Non-Games visitors tickets were also sold, therefore the average number of visitors to the Park was estimated to be 325,000. The event lasted for 25 days, therefore the estimated total number of visitors to the park is 8,125,000. The total number of officials, media, athletes and employees during the Games is estimated to be approximately 318,000, with approximately 58-63% being employees and 25-30% being athletes and their families (London2012, 2009).

It is possible to estimate the approximate number of officials and athletes during a mega-event, however it is very difficult to evaluate the exact number of visitors to a host city and their origin. It is possible to estimate the approximate number based on the information for the previous events of such scope. Table 6.3 provides the details on the visitors' origin. The visitors' origin during the event is based on the Tranport plan of the Candidate File (GLA, 2004); the origin of the visitors in the legacy phase is assumed based on the fact the majority of them will be from London or the UK.

Table 6. 3. Assumptions relating to visitors' origin (% of the total number of visitors) (based on the GLA, 2004).

Visitors' origin	London area	UK	Europe	Rest of the World (RoW)
Event	20-30%	40-50%	20-30%	3-10%
Legacy	60-70%	20-30%	10-15%	1-3%

It is difficult to determine precisely the number of the event visitors travelling by each transport mode before the event. However, based on the data on general visitors to the city, capacities of various transport modes and other factors it is possible to assume the minimum and maximum number of visitors using each transport mode. Table 6.4 provides the estimated range of transport mode split for all types of the event visitors.

Table 6. 4. Estimated transport mode split for all types of the event visitors (% of the total in each visitor's origin category) (based on the GLA, 2004).

Transport mode	London	UK	Europe	Rest of the World	Athletes	Media	Officials	Employees	Travel Grant
Car	5-15%	28-35%	7-15%						
Long-haul flight-economy				85-90%	25-35%	25-35%	15-20%		88-93%
Long-haul flight-first class							10-15%		
Short-haul flight-economy			47-55%	10-20%	60-70%	60-70%	35-45%		10-15%
Short-haul flight-business			10-15%				25-30%		
UK domestic		2-5%							
London bus	1-3%							10-20%	
Rail	70-80%	50-60%			5-10%	5-10%		75-85%	
Coach	8-13%	6-13%	6-14%						
Eurostar			5-12%						
Cycle	2-6%							3-7%	
Ferry			7-10%						

During the event period, a certain number of the official vehicles are provided for the use by sponsors, athletes and families, media and other official staff. We have assumed that the total number of all types of vehicles is 5200 and the constraint is the minimum and maximum number of different vehicle types. Table 6.5 provides the estimated mode split for the 'official' transport during the event period.

Table 6. 5. Estimated data for the 'officials' transport during the event period.

Vehicle types for the 'officials' transport	Minimum number of vehicles available	Maximum number of vehicles available	Duration of usage (days)	Fuel usage (litre/day)	Assumed Petrol/Diesel Ratio
Cars- Games time	2300	3500	660	10	0.7/0.3
Coaches – officials	600	1500	40	160	0/1
Mini-buses	200	300	40	160	0/1
Motorcycles	10	30	60	10	0.5/0.5
Boats	30	40	10	10	0/1

Coaches-sponsors	300	450	60	60	0/1
Village and Park vehicles	20	40	60	10	0.5/0.5

It was estimated that during the construction phase 459,000 tonne of materials and construction waste were transported to/from the site of the Olympic Park. One of the objectives in the London 2012 Olympics Sustainable Developed Strategy (London2012, 2007a) was to transport at least 50% of the total amount of waste and materials by rail and by water. This objective is incorporated in the model described in section 6.5 as a sustainability constraint. It is assumed that the same constraint is applied for the baseline post-event scenarios in the legacy phase.

6.3.2. Proposed design scenarios of the event site in the legacy phase.

It was mentioned earlier that the post-event legacy phase of a mega-event project will result in long-term environmental, economic and social impacts of much higher magnitude that the construction phase and staging of the event. Therefore, it is vitally important to ensure early planning of the post-event design scenarios and integrate the process with a city development plan.

In this project, 3 potential post-event site design scenarios were developed to test the robustness of the proposed methodology as described in the section 4:

- ‘Business as Usual’ (BAU) scenario;
- ‘Commercial World’ (CW) scenario;
- ‘High rise, high density scenario’ (HRHD) scenario.

The estimations and assumptions on the number and type of different venues in each scenario are provided in Appendix 2. Table 6.7 provides the summary of the total floor areas and footprints of all buildings for each of the proposed post-event site scenario. Table 6.6 provides the summary of the number and type of buildings for each baseline scenario.

Table 6. 6. Estimated number of different types of new residential and non –residential buildings for each of the 3 baseline post-event scenarios (excluding the venues built for the event).

	BAU scenario	CW scenario	HRHD scenario
Residential units	6,800	1000	16,000
Commercial offices	2 13-storey offices, 4 small industrial units	15 13-storey offices, 30 small industrial units	15 25-storey offices, 15 30-storey offices, 10 small industrial units
Community centres	2	1	7
Retail/supermarket space	3	5	15
Restaurants	40 fast food, 40 medium size restaurants	50 fast food, 20 medium size restaurants	100 fast food, 30 medium size, 10 large restaurants
Hotels	1 10-storey	5 10-storey	5 20-storey

Table 6. 7. Estimated total floor area (m^2) and footprint area (m^2) of each type of new development for the 3 baseline post-event site design scenarios (does not include the existing infrastructure of the Olympic Park).

Size of each type of venue	BAU scenario	CW scenario	HRHD scenario
Total internal floor area of all residential buildings (m^2)	638,194	70,000	898,000
Total footprint area of all residential buildings (m^2)	408,800	7,000	53,880
Total internal floor area of commercial buildings – offices (m^2)	46,200	4,180,500	2,132,475
Total footprint area of commercial buildings – offices (m^2)	7,876	346,500	128,150
Total internal floor area of retail buildings (m^2)	22,590	37,650	112,950
Total footprint of retail buildings (m^2)	15,813	26,355	75,676
Total internal floor area of hotel buildings (m^2)	16,800	84,000	168,000
Total footprint of hotel buildings (m^2)	3,360	8,400	13,200
Total internal floor area of community facilities and social infrastructure (m^2)	76,193	29,488	102,621
Total footprint of community	37,825	15,386	36,811

facilities and social infrastructure (m^2)			
Total floor area of all new buildings (m^2)	**799,977**	**4,401,638**	**3,405,046**
Total footprint of all new buildings (m^2)	**473,674**	**403,641**	**307,717**

It is assumed that the following venues from the event site will be permanently in operation in the legacy phase:

- The Olympic Village – residential buildings (one- and two-bedroom apartments);
- The Broadcast and Media Centres – office buildings;
- The Olympic Stadium (reduced capacity);
- The Aquatic Centre;
- Hockey Centre;
- Velodrome;
- Handball Arena.

The estimated annual number of spectators, competitors and staff for all sports venues in the legacy phase is based on the estimated number of competitions per year and provided in Appendix 1. The total number of employees and residents for each post-event scenario depends on the number and type of the residential buildings and commercial ofices on site and will be determined in the models. The data on each of the baseline post-event scenarios is provided in Appendix 2. The total number of visitors for sporting events depends on the number of permament sport venues which will be in operation in the legacy phase. For the baseline post-event scenarios, it is assumed that the 5 permanent sport venues specified above will be in operation. The annual number of general visitors to the park in the legacy phase is assumed to be 1,000,000; 500,000 and 2,000,000 for the BAU, CW and HRHD scenarios respectively. The visitors' number were estimated for the BAU scenario by the London Legacy Development Corporation (LLDC, 2014). The visitors' numbers for the CW and HRHD scenarios were estimated based on the assumptions that HRHD will attract more visitors than the CW due to a higher number of pubic amenities.

The models described in sections 6.4 – 6.6 provide the information regarding the environmental impacts of various phases of a mega-event project that can be used by the decision-makers in order to evaluate the outcomes of the proposed baseline scenarios and determine how to optimise them in order to minimise the environmental burdens. The results regarding the operation of the post-event sites are presented for the first year only and assumed to remain the same throughout the whole legacy phase. The results for the construction and the event are presented for the overall duration of the phases. The issue of building maintenance is not considered in this work. In section 6.7, the overall results for each baseline and optimised scenario are presented for the duration of the whole life cycle of the project: construction, staging the event and the legacy phase. The duration of a legacy phase is assumed to be 25 years from the re-opening of the site after its post-event redevelopment. Environmental impacts resulting from the transportation, water and energy are expressed in tonnes of CO_2 equivalent (CO_2-eq).

Each scenario has its advantages and drawbacks and a combination of many social, environmental and economic aspects have to be considered and evaluated before making a final decision. The HRHD scenario, for example, is the best alternative in terms of land utilisation due to the high-rise buildings. This can be considered as a very important aspect in many large cities like London where land is at a premium. The CW scenario can be a good solution for London because of the great public transport links to the Olympic Park and high demand for commercial offices. The BAU scenario is based on the current strategy of the development of the Olympic Park (LLDC, 2012). It represents a typical London development that is comprised of a mixture of low-rise apartment blocks and terraced and semi-detached houses. It can be seen that although the total footprint of the buildings in this scenario is the largest compared to the other two scenarios, the total floor area of all buildings is much smaller than in the other two scenarios. Hence, the BAU scenario is definitely the worst alternative in terms of land utilisation. However, it can be argued that the BAU scenario is based on the type of development that is characteristic for London and, therefore, may be preferred and supported by the city residents and authorities. However, this might not be the case for another city or country where the CW, HRHD or another scenario might be the preferred option.

6.4. Optimising embodied emissions from the building materials.

6.4.1. Description of the model and the results for the baseline scenarios.

Materials used in construction have different amounts of embodied GHG emissions associated with their extraction, refining, manufacture and delivery. It is estimated that the production of cement and steel alone account for over 10% of global annual GHG emissions (ECCM, 2006). The focus of the UK Building Regulations (BRE, 2006) has been on the operational energy use while the embodied energy of construction materials has not been addressed in the legislations (Densley Tingley and Davison, 2010). It is argued that in many cases reductions in operational energy of buildings leads to the increased percentage impact of the embodied energy (Vukotic et al., 2010). Therefore, it has been emphasised that although there is no current legislation to encourage the minimisation of embodied emissions of construction materials, it is important to adopt a life cycle approach when considering the total energy/carbon of a building and evaluate the embodied emissions (Hernandez and Kenny, 2010; IGT, 2010). Life cycle approach is applied and this work; therefore, both embodied GHG emissions from the construction materials and GHG emissions associated with energy use in buildings (section 6.6) have been taken into account.

Problem formulation.

The problem can be formulated as a single-objective optimisation problem as follows:

$$\min_{x} F(x) \qquad (6.1)$$

$$\text{s.t.} \quad h(x,u)=0$$
$$g(x,u) \leq 0$$

where F is the objective function, the equations h are equality constraints, the equations g are inequality constraints, x are design variables, u represents fixed parameters that are not modified during the calculations.

The objective is to minimise the total GHG emissions associated with the construction materials of all venues for the event phase and all post-event buildings in the legacy phase, subject to constraints. The emissions are calculated based on the type of construction materials (virgin or recycled), availability of recycled and reclaimed materials, transportation distances for recycled materials, and emissions conversion factors for each type of material, subject to constraints. The models were implemented in GAMS 24.0.1 on a 64-bit Windows 8 machine using CONOPT solver.

Mathematical formulation.

The problem is formulated as a static, single-objective, linear programming (LP) model with the following notations:

Indices

b All types of buildings including sports venues, site infrastructure built for the event and for the legacy phase

m Materials used for the construction of the venues

Sets

B Set of all types of buildings (sports venues, residential buildings, commercial offices, other amenities)

M Set of all materials used for the construction of buildings (see Appendix 1)

R Subset of set M including only recycled or reclaimed materials

Parameters

E_m Emissions conversion factor for each type of virgin construction materials (kg CO_2-eq kg^{-1} of material)

E_r Emissions conversion factor for each type of recycled or reclaimed construction materials (kg CO_2-eq kg^{-1} of material)

D_m Transportation distances of all materials (km)

D_r Maximum transportation distances of recycled or reclaimed materials before the emissions conversion factor of these materials becomes equal to the emissions conversion factor of virgin materials (km)

Q_{mb} Quantity of each type of material *m* (tonnes) used for the construction of each type of building *b*

A_m Amount of all materials used for the construction (both new and recycled or reclaimed)

Positive variables

F_r Maximum total amount of recycled or reclaimed materials available (fraction of the total amount of materials required)

A_r Amount of recycled or reclaimed materials used

Continuous variables

G_{mb} Amount of GHG emissions resulting from each type of material *m* used in each types of buildings *b*

EM Total amount of GHG emissions resulting from construction of all types of buildings

Constraints

- ***Supply constraint***

The amount of recycled or reclaimed materials A_r (tonnes) used in all types of buildings *b* is calculated based on the maximum amount of recycled or reclaimed materials available represented by the fraction F_r in regards to the total amount A_m (tonnes):

$$A_r = A_m F_r \qquad \forall r \in R, m \in M \tag{6.2}$$

- ***Transportation distance constraint***

Emission conversion factors for recycled or reclaimed construction materials E_r normally have values lower than the values for new materials E_m. However, if the transportation distance D_r of a recycled material exceeds a certain distance D^{max}, then the value of the emissions conversion factor for the recycled material becomes the same as the emissions conversion factor for the new material. Thus, it is assumed that after a certain maximum distance D^{max} (which is different for each type of recycled or reclaimed material) only virgin materials are used.

$$D_r \leq D^{\max} \qquad \forall r \in R \tag{6.3}$$

Objective function –materials.

The objective function is based on the minimisation of the total GHG emissions resulting from all construction materials *m* used in all types of buildings *b* and is formulated as follows:

$$EM = \sum_{m \in M} \sum_{b \in B} G_{mb} E_m \tag{6.4}$$

where G_{mb} is the total amount of emissions from all types of materials *m* used in all types of buildings *b* and E_m is the emissions conversion factor for each type of material *m*.

Assumptions:

- Amount and types of materials required for the construction of the event and post-event venues were estimated based on the data for different types of buildings gathered from various literature sources (see Appendix 1).
- Distances for materials transportation in the post-event phase are assumed to be the same as in the event phase for each material type (see Appendix 1).
- Embodied carbon for each type of material was estimated using the 'Inventory of carbon and energy (ICE)' (Hammond and Jones, 2008). Embodied carbon is expressed in kg CO_2-eq.

- It is assumed that the maximum amount of recycled material (as a percentage of the total amount of material required for the construction) in each scenario is 10% for steel, 20% for aluminium and 15% for timber.

Computational results.

The model has been applied to a case study of the London Olympic Park evaluating embodied emissions from the construction of venues and infrastructure for the event site and embodied emissions from 3 proposed scenarios of the post-event site redevelopment. The data for materials for each type of buildings and emissions conversion factors is provided in Appendix 1. Table 6.8 provides the total quantity of building materials used for the construction of the event site and for the redevelopment of the post-event site in each of the 3 baseline legacy scenarios.

Table 6. 8. Estimated quantity of construction materials used for the construction of the event site and the proposed post-event legacy scenarios.

	Construction of event venues and infrastructure	Legacy		
		BAU scenario	CW scenario	HRHD scenario
Estimated quantity of construction materials used (ktonne)	3,603	5,563	4,060	8,236

Table 6.9 provides the results of the embodied GHG emissions associated with preparation of the site for the event and construction of venues and infrastructure. It can be seen that transport infrastructure results in more than 40% of the total emissions associated with the construction of the event site. Emissions associated with construction of the Olympic Village result in almost 25% of the total emissions, and emissions associated with materials used for the Broadcast and Media centres result in 10% of the total emissions from materials.

It can be argued that emissions associated with construction materials for the event are high considering the duration of the event (total 77 days for the London 2012 Olympics). Therefore, the early planning of the post-event scenarios is crucial at the earliest stages of the project in order to ensure that the majority of permanent venues and transport infrastructure built for the event are used in the post-event legacy phase. It is also important at the early stages of the project to decide how temporary buildings will be removed from the site, where they will be used after the event and what materials are should be used to reduce their environment impacts. Emissions resulting from the demolition of the buildings vary and account for approximately 5-10% of the GHG emissions associated with the total building's life cycle (Bayer et al., 2010). These values may vary depending on the type and size of a building, energy and transport used, and many other factors. In this project, the GHG emissions associated with the demolition and re-use of the temporary buildings and with the demolition of the permanent venues in the end of their life cycle are not accounted for.

Table 6. 9. Embodied GHG emissions from the construction of the event site and infrastructure.

Event venues and infrastructure	Total embodied carbon (t CO_2-eq)
Olympic Stadium	74,936
Broadcast Centre	101,274
Media Centre	39,778
Aquatic Centre	52,356
Olympic Park utilities	23,294
Olympic Park structures	137,457
Cabling and tunnelling	42,028
Energy Centre	3,615
Olympic Village	373,864
Olympic Torches	73
Cauldron	40
Transport Infrastructure	590,000
Total	**1,438,716**

Tables 6.10-6.12 provide the results of the estimated embodied emissions for each of the proposed 3 post-event site design scenarios.

Table 6. 10. Embodied GHG emissions from the venues construction for the BAU scenario.

Venue type	Total embodied carbon (t CO_2-eq)
Typical UK houses	83,207
Apartment blocks	12,249,400

Typical London offices	524,923
Small industrial units	1,061,409
Supermarkets/retail	617,671
Hotels	95,180
Schools	546,033
Medical Centres	66,044
Restaurants	380,642
Community Centres	20,855
Total	**15,645,364**

Table 6. 11. Embodied GHG emissions from the venues construction for the CW scenario.

Venue	Total embodied carbon (t CO_2-eq)
Apartment blocks	3,062,362
Typical London offices	3,936,924
Small industrial units	7,960,568
Supermarkets/retail	1,029,450
Hotels	475,898
Schools	189,438
Medical Centres	22,911
Restaurants	224,186
Community Centres	10,428
Total	**16,912,165**

Table 6. 12. Embodied GHG emissions from the venues construction for the HRHD scenario.

Venue	Total embodied carbon (t CO_2-eq)
High rise residential	26,870,200
High rise office buildings	21,864,100
Small industrial units	2,653,523
Supermarket	3,088,356
Hotels	2,687,024
Schools	988,022
Medical Centres	119,519
Restaurants	574,237
Community Centres	72,993
Total	**58,917,974**

From tables 6.10-6.12 it can be seen that the embodied emissions from the materials used for the construction of the HRHD scenario are approximately 3 times higher than those resulting from the construction of buildings in BAU and CW scenarios. This can be explained by the fact that in HRHD scenario the high-rise development leads to a higher number of residential units, commercial offices and other amenities on site compare to the other two scenarios and, therefore, larger quantities of building materials used for the construction.

Figures 6.2-6.4 provide the total embodied emissions for each of the 3 scenarios including emissions from the construction of venues and infrastructure for the event. It can be seen that in BAU and CW embodied emissions associated with the construction of the event site result in 9% and 8% of the total embodied emissions respectively. In HRHD scenario, embodied emissions from the event site constructions account only for 2% of the total embodied emissions. This is due to the larger quantities of building materials required for the construction of the post-event buildings in this scenario.

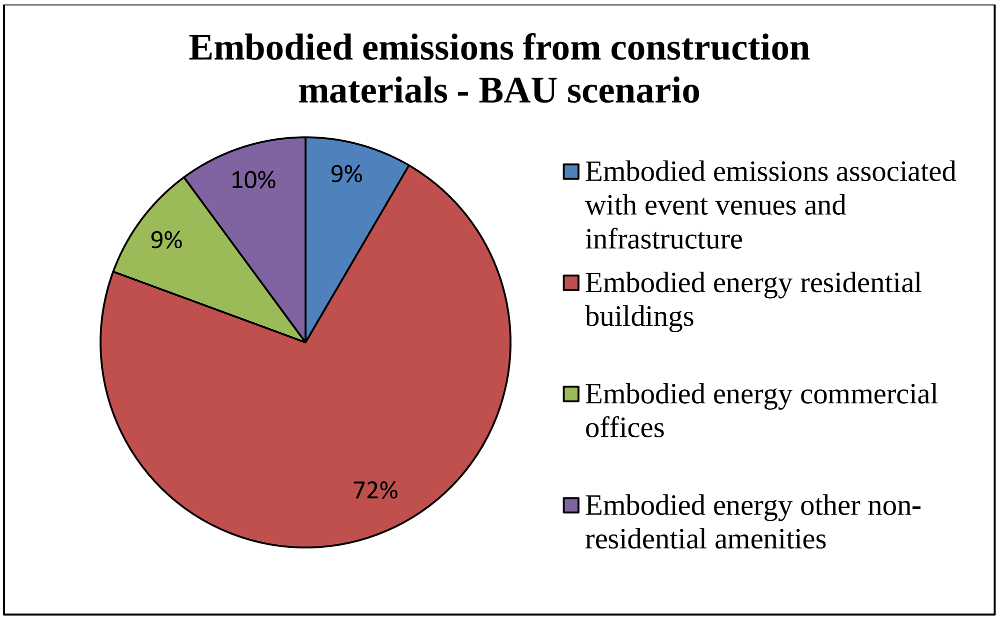


Figure 6. 2. Embodied emissions from construction materials – BAU scenario (including the event venues and infrastructure).

Total embodied emissions from the construction materials for the CW scenario are 8% higher than those for the BAU scenario. From figures 6.2 and 6.3 it is obvious that the majority of the embodied emission in BAU scenario (72%) is associated with the materials for the construction of residential buildings while embodied emissions associated with the construction materials of the new offices account for 9% of the overall embodied emissions. On the contrary, the majority of embodied emissions in the CW scenario (65%) come from the materials for the new offices while embodied emissions from residential buildings account for 17% of the total emissions. The embodied emissions associated with construction of other on-site amenities account for 10% of the total emissions for the BAU and CW scenario and 12% for the HRHD scenario.

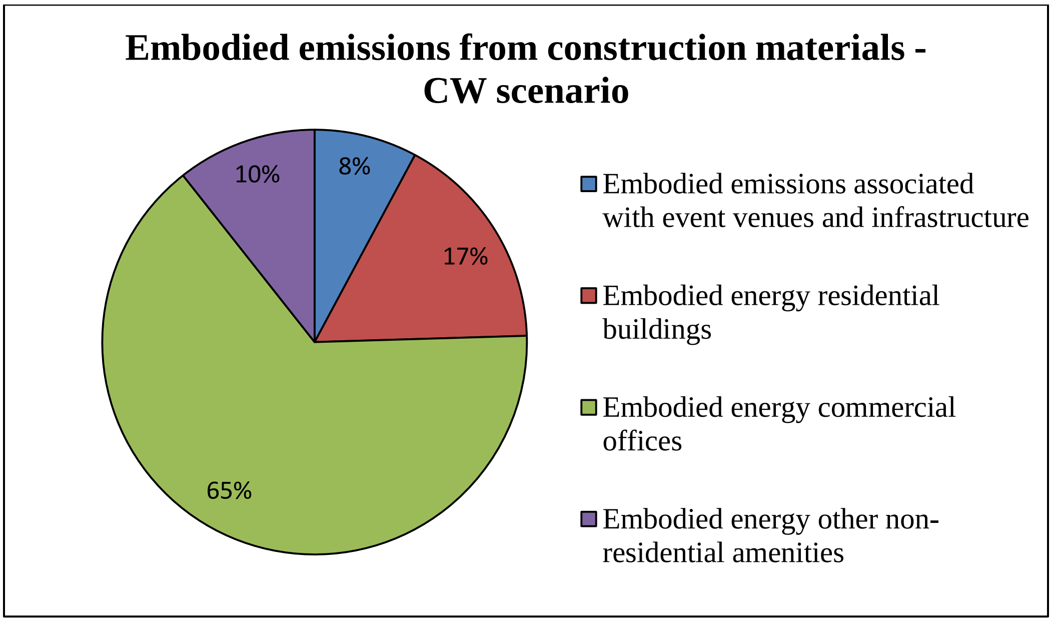


Figure 6. 3. Embodied emissions from construction materials – BAU scenario (including the event venues and infrastructure).

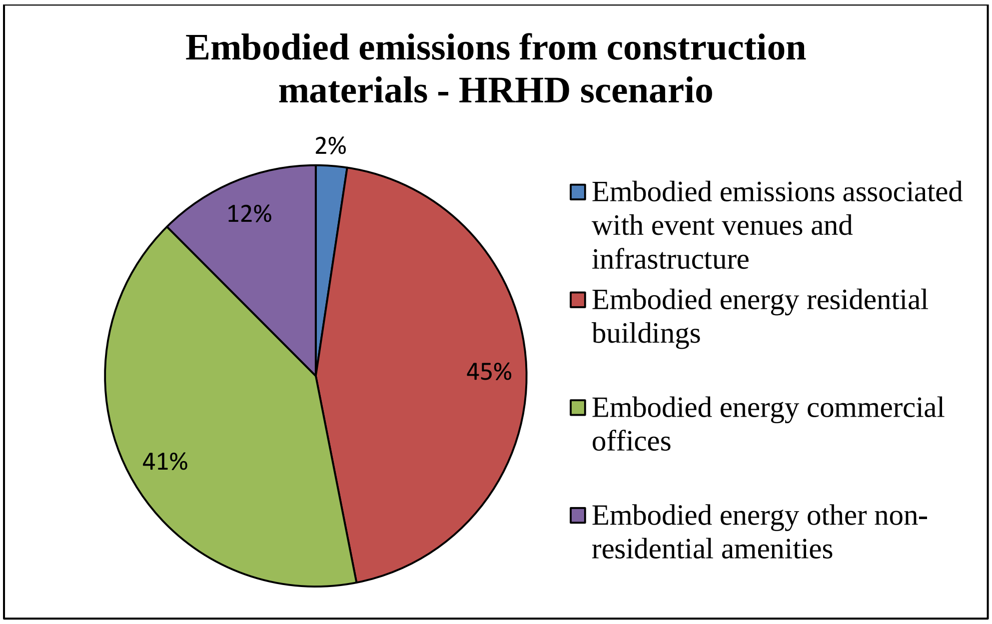


Figure 6. 4. Embodied emissions from construction materials – HRHD scenario (including the event venues and infrastructure).

These results can be used during the planning process to identify the embodied emissions associated with the construction of different building types. For example, it is clear that the majority of the embodied emissions in CW scenario come from the construction of commercial offices. Therefore, the focus should be primarily on reducing the embodied emissions associated with materials used for the construction of the offices.

The results can also be used by the decision-makers as a starting point in the development of a sustainability strategy for a mega-event project. First, the embodied emissions are calculated based on the typical construction practices. Next, sensitivity analysis is carried out in order to identify which parameters have the highest impact on the overall performance of the system. Finally, the embodied emissions can be optimised based on the results of a sensitivity analysis and sustainability targets. Section 5.4.1 provides the results of a sensitivity analysis carried out for the 3 proposed post-event site scenarios which show how changes in the quantities of some recycled materials affect the overall materials emissions.

6.4.2. Sensitivity analysis – building materials.

Sensitivity analysis is normally carried out with the purpose of identifying which parameters have the highest impacts on the overall results. By identifying those parameters the system can be optimised to improve its performance. In this section, the results of the sensitivity analysis demonstrate how the total quantity of the embodied emissions from construction materials can be optimised by changing the quantities of different recycled materials. Table 6.13 provides the data on the availability of recycled materials in the original scenarios described in section 6.4.1 and in two other alternatives examined in the sensitivity analyses M1 and M2. It is assumed that the same data is applied to all 3 scenarios considered in this work.

Table 6. 13. Quantities of recycled materials available originally and in two other alternatives examined in the sensitivity analyses M1 and M2. The same data is applied to all post-event site scenarios.

Amount of recycled materials available (percentage of the total amount of materials)	Original scenarios	Sensititivy analysis - M1	Sensititivy analysis - M2
Steel	10%	20%	10%
Aluminium	20%	30%	40%
Timber	15%	25%	15%

Figures 6.5 - 6.7 provide the results of the sensitivity analysis for each of the proposed design scenarios. It should be noted that the embodied emissions from the construction materials of all life cycle stages of a mega-event project are included for each scenario.

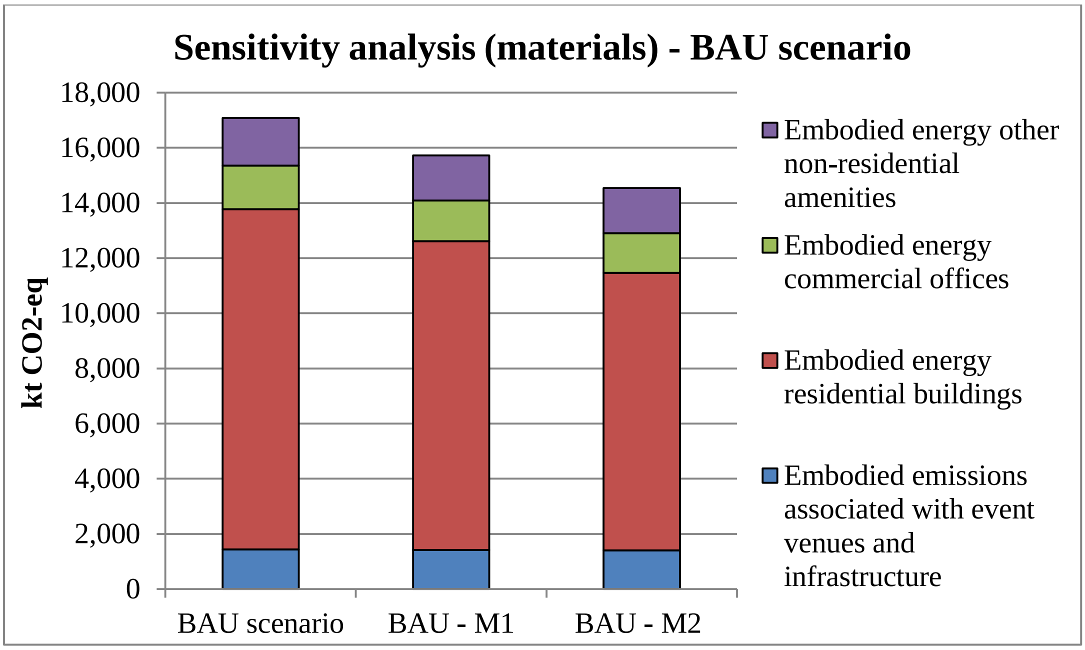


Figure 6. 5. Sensitivity analysis (construction materials) – BAU scenario.

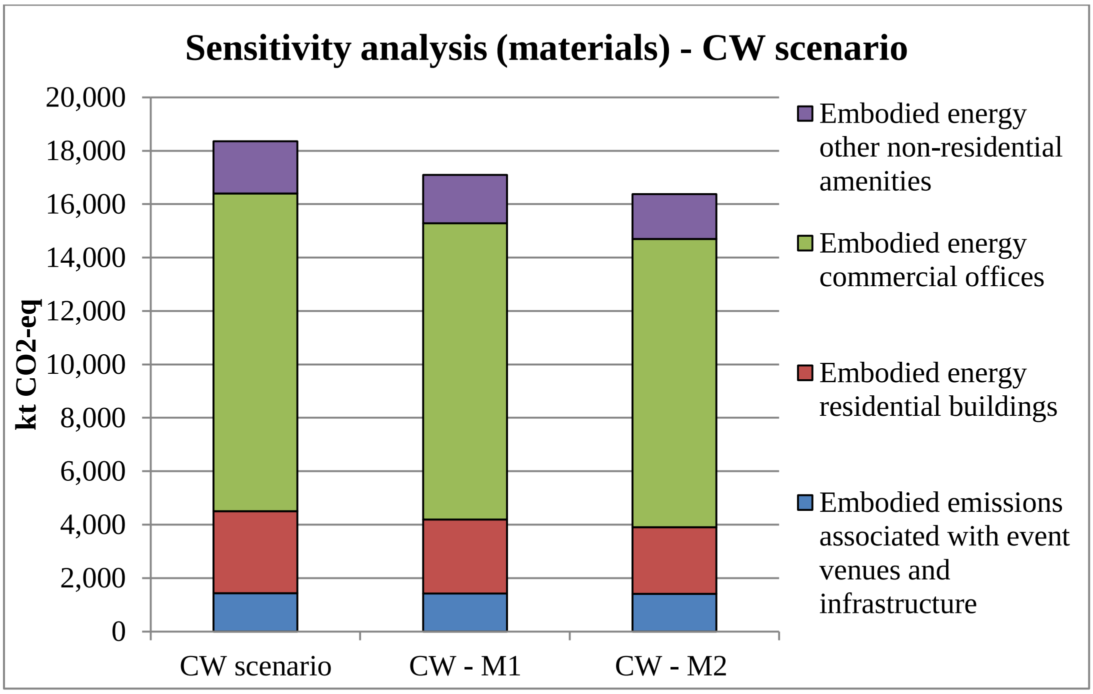


Figure 6. 6. Sensitivity analysis (construction materials) – CW scenario.

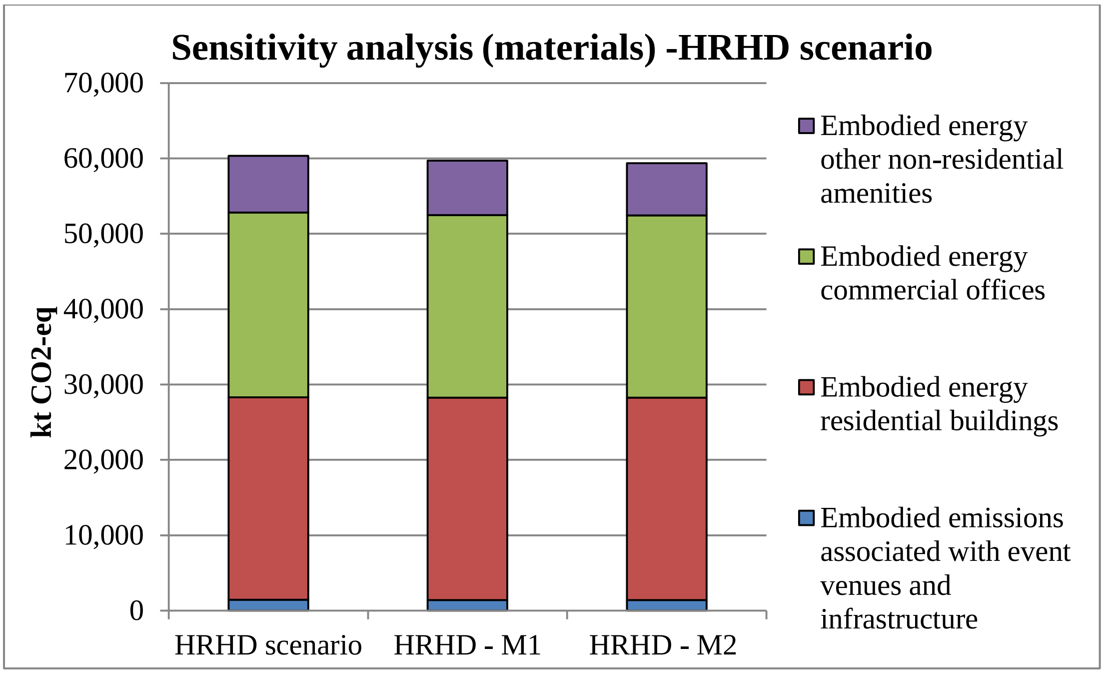


Figure 6. 7. Sensitivity analysis (construction materials) – HRHD scenario.

It is obvious that the increase of the quantity of recycled materials leads to the decrease of the total embodied emissions from construction materials (assuming that the constraints described in section 6.4.1 are satisfied). The results of the sensitivity analyses show that the highest total embodied emissions reduction is achieved in the case of doubling the amount of recycled aluminium compared to the original amount. It can be seen that in this case the total emissions are reduced by 15 and 11% respectively for the BAU and CW scenarios (M2). The total emissions reductions can also be achieved by increasing the amount of each recycled material by 10% compared to the original amount. In the BAU and CW scenarios the emissions are reduced by 8 and 7% respectively (M1). This can be explained by the lower value of the emissions coefficient for recycled materials compared to the virgin materials. For example, the emissions coefficient for the production of 1 kg of virgin aluminium is 11.46 kg CO_2-eq/kg while the emissions coefficient for the production of 1 kg of recycled aluminium is 1.69 kg CO_2-eq/kg (Hammond and Jones, 2008). All emissions coefficients used in this work are provided in Appendix 1.

In the HRHD scenario, the total embodied emissions are reduced only by 1% in M1 and by 2% in M2 compared to the original scenario. This is due to the fact that the construction materials in this scenario are different from those required for the BAU and CW scenarios because of the different specifications of the high-rise buildings. In these buildings the main materials used are steel and concrete. The difference between the values of the emissions coefficients for virgin and recycled steel is not as large as for the aluminium (2.75 vs 0.43 kg CO_2-eq/kg); therefore, increasing the quantity of recycled steel does not reduce the overall emissions by the same percentage as the increased quantity of recycled aluminium.

6.4.3. Baseline vs optimum scenarios – building materials.

In section 6.4.1 the embodied emissions from all construction materials were calculated for each site design scenario based on the constraints of the maximum quantity of the following recycled materials available: aluminium, steel, stone, timber, tiles and bricks. In order to determine the optimum scenarios, the constraints on the availability of recycled materials were removed. As a result, in the optimum scenarios the share of all recycled materials has been maximised to 100%. Figure 6.8 shows the results of the total embodied emissions resulting from building materials for baseline and optimum scenarios.

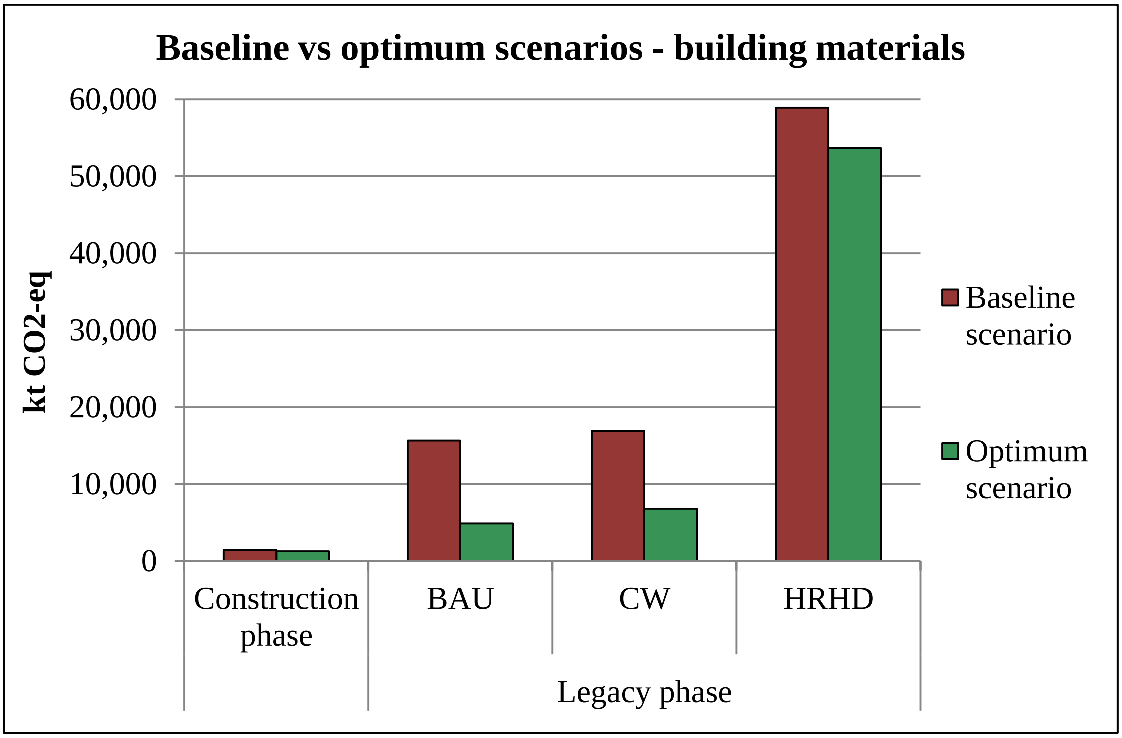


Figure 6. 8. GHG emissions from building materials – baseline vs optimum scenarios.

It can be seen that the total embodied emissions for the optimum scenarios are lower than for the baseline scenarios, particularly for the BAU and CW scenarios. The GHG emissions resulting from the construction phase can only be reduced by approximately 10%, which is also the case for the HRHD scenario. This can be explained by the fact that during this phase the main construction materials are different types of concrete and cement. Although concrete can be recycled and used as gravel on the construction site, it cannot be used in the same way as recycled aluminium or wood. Many other types of building materials can also be recycled and utilised further instead of other materials. However, they cannot substitute virgin material.

6.5. Optimising emissions from the transportation of visitors and materials.

6.5.1. Description of the model and the results.

Selecting a location for a mega-event site is an opportunity to consider a number of important issues such as access to transport. Accessibility to reliable public transport is of increasing interest to event organisers (Laing and Frost, 2010). Robbins et al. (2007) note that travel is a key issue for event management due to the effect transport can have on GHG emissions, as well as other negative impacts of a more local nature, predominantly those focused on the use of cars to reach the event venue such as air quality, noise and congestion. Moreover, public transport system is extremely important in the long-term legacy phase as it will help to reduce transport emissions and provide easy access to the site. The model described in this section takes into account the emissions associated with the transportation of visitors and materials throughout the whole project's life cycle.

Problem formulation.

The problem can be formulated as a single-objective optimisation problem as defined in the set of equations 6.1.

The objective is to minimise the total GHG emissions associated with the transportation of the building materials and waste during the site preparation and construction of the event venues, transportation of all visitors and officials during the event phase, transportation of the building materials during the post-event site redevelopment and transportation of the residents and visitors to/from the site during the first year of the legacy period. The emissions are calculated based on the transport modes for the visitors and officials, visitors' categories, total number of visitors and officials, average distance travelled by each visitors' category, modes of transport for materials and construction waste, amount of materials and waste, specific GHG emission factors for each mode of transport, subject to constraints.

Mathematical formulation.

The transportation section is formulated as a static, single-objective, non-linear programming (NLP) model with the following categorisations:

Indices:

v Transport modes for all visitors

o Transport modes for all officials

w Transport modes for waste and materials

c Visitors' origin category

f Types of vehicle fuel for official vehicles

s Transportation sectors

Sets:

V Set of transport modes for all visitors (long- and short-haul flight (economy and business), domestic flight, petrol car, bus, rail (includes overground and underground), coach, Eurostar train, ferry, bicycle)

O Set of transport modes for all officials during the event (cars-officials, coach-athletes, coach-sponsors, bus, motorcycle, boat, village and park vehicles)

W Set of transport modes for all construction waste and materials (lorries, barges, rail)

C Set of categories of visitors to the Olympic Park by origin (London, UK, EU, Rest of the World (RoW), athletes, media, officials, employees, travel grant)

F Set of vehicle fuel types for the official vehicles (petrol, diesel)

S Set of the transportation sectors (visitors, officials, materials and waste)

Parameters:

E_v Emissions conversion factor for each visitors' transport mode (kg CO_2-eq km^{-1})

E_o Emissions conversion factor for each type of fuel for official vehicles (kg CO_2-eq l^{-1})

E_w Emissions conversion factor for each type of transport mode for the construction materials and waste (kg CO_2-eq km^{-1})

D_c Average transportation distance for each type of visitors and officials (km)

D_w Average transportation distance for construction waste and materials for each type of transport mode (km)

F_f Average daily amount of fuel used in different types of official vehicles (litres)

N_v Total number of all visitors, athletes, media and officials to the Park (number of people)

A_w Total amount of construction waste and materials transported (tonnes)

U_o Duration of usage of each type of the official vehicles (days)

Positive variables:

X_{vc} Fractions of each visitor origin type *c* travelling by each transport mode *v*

Y_{of} Fractions of different official vehicles *o* according to their fuel type *f*

Z_w Fractions of total construction waste and materials *m* transported by different transport modes *v*

V_o Quantities of various types of official vehicle available

Continuous variables:

ET_o Total amount of GHG emissions from the official vehicles (kg CO_2-eq)

ET_c Total amount of GHG emissions from visitors' transportation (kg CO_2-eq)

ET_w Total amount of GHG emissions from the transportation of construction materials and waste (kg CO_2-eq)

Constraints:

- ***Visitors' constraints***

The exact number of visitors and their origin cannot be calculated exactly for any event; however, the numbers can be estimated based on the data for similar past events. The minimum and maximum quantities of visitors in each category are represented as fractions in regards to the total number of visitors. A sum of all fractions of visitors in each visitor's category is equal to 1. Thus, visitors' constraint is defined as follows:

$$\sum_{c \in C} X_c = 1 \tag{6.5}$$

where X_c is the fraction of each visitor origin type *c*.

- ***Transportation constraints***

There are various vehicles types provided for the transportations of officials (including media and athletes) during the event. Assume that there are different types of official vehicles are available but the total number of all vehicles does not exceed a certain quantity V_o^{max}.

$$\sum_{o \in O} V_o = V_o^{\max} \tag{6.6}$$

where V_o^{max} is the maximum quantity of all types of official vehicles available during the event phase.

- ***Sustainability constraint***

Sustainability constraint for materials transportation is based on the 'Sustainable Development Strategy' for the London Olympic Park (London2012, 2007b) and defined as follows: the minimum amount of construction materials and waste that has to be transported by rail and/or barges has to be 50% of the total amount of construction materials and waste transported. This sustainability constraint is applied for the baseline scenarios. In section 6.5.3 the constraint will be removed to investigate what is the best transportation option in the optimum scenarios.

$$Z_{w(rail)} + Z_{w(barge)} \geq 0.5 \tag{6.7}$$

where $Z_{w(rail)}$ and $Z_{w(barge)}$ are the fractions of the total amount of materials and waste transported.

Objective function

The objective function is based on the minimisation of the total emissions during the construction, staging the event and post-event site operation (*TET*) associated with all types of transportation.

Minimise TET

s.t. Visitor' and officials' constraint

Transportation constraint

Sustainability constraint

The total emissions resulting from the transportation are calculated by:

$$TET = \sum_{s \in S} ET_s \tag{6.8}$$

where ET_s is the transportation emissions resulting from each sector s. Sectors s include emissions from the official vehicles (ET_o), emissions from transportation of all visitors to the site including transportation to and within a host city (ET_c), emissions from transportation of construction materials and waste (ET_w).

The total emissions resulting from the official vehicles before and during the Games are calculated by:

$$ET_o = \sum_{o \in O} \sum_{f \in F} Y_{of}\ E_o\ F_f\ V_o U_o \tag{6.9}$$

where o is the set of official vehicle by type, f is the set of official vehicles by their fuel type, F_f is the average amount of fuel used in different types of official vehicles (litres), U_o is the duration of usage of each type of the official vehicles (days), E_o is the emissions conversion factor for the official vehicles (kg CO_2-eq l^{-1}), Y_{of} are the fractions of different official vehicles according to the fuel types, V_o is the number of different official vehicle types.

The total emissions resulting from the transportation of all visitors to/from London and to/from the Olympic Park, including transport of all officials to/from London are calculated by:

$$ET_c = \sum_{v \in V} \sum_{c \in C} D_c\ E_v\ X_{vc}\ N_v \tag{6.10}$$

where c is the set of different categories of visitors by origin, v is the set of different visitors' transport modes, D_c is the average distance travelled by each type of visitor (km), E_v is the emission conversion factor per each mode of transport (kg CO_2-eq l^{-1}), X_{vc} is the fraction of each visitor origin type c travelling by each transport mode v, N_v

is the total number of all visitors. This includes all types of visitors to the site during the event, general visitors to the site and visitors for sporting events in the post-event period.

The total emissions resulting from the transportation of all materials and construction waste to/from the site during the construction stage is calculated by:

$$ET_w = \sum_{w \in W} D_w \, E_w \, Z_w \, A_w \tag{6.11}$$

where D_w is transportation distance for materials and waste by each transport mode (km), E_w is the emission conversion factor of each transport mode (kg CO_2-eq l^{-1}), Z_w is the fraction of materials and waste transported by each transport mode, A_w is the total amount of materials and waste transported.

Assumptions:

- All transport assumptions in regards to the number of visitors, their origin, transport modes and distances travelled were estimated based on the Candidate File (GLA, 2004).
- Average distance travelled by each visitor's category is assumed to be a return trip.
- Total number of officials, media, athletes, and employees during the Games period and the number of official vehicles, their types and duration of use are estimated based on the Candidate's File (GLA, 2004).
- The range of each visitor's origin group is estimated based on the Candidate File (GLA, 2004).
- Assume that non-London visitor's trip includes a return trip from the destination of origin to London plus one return trip within London (assume the allocation of transport modes within London being the same for all groups of visitors).
- Assume the maximum total quantity of all official vehicles during the event is 4200 (London2012, 2007b).
- Transport modes considered in this project are specified in Table A29.

Computational results.

Figure 6.9 present the results of the estimated emissions associated with the transportation of visitors and officials during the event, transportation of construction materials during the event site construction and post-event site redevelopment, and transportation of visitors in for the first year of the legacy period. In sections 6.5 and 6.6 the emissions for the legacy period are calculated only for the first year. This value can serve as a benchmark to improve the performance in the subsequent years. In this work we assumed that the GHG emissions values stay constant for each year of the legacy period. The results presented in section 6.7 provide the total GHG emissions values for the whole life cycle of the project including the total duration of the legacy phase – 25 years.

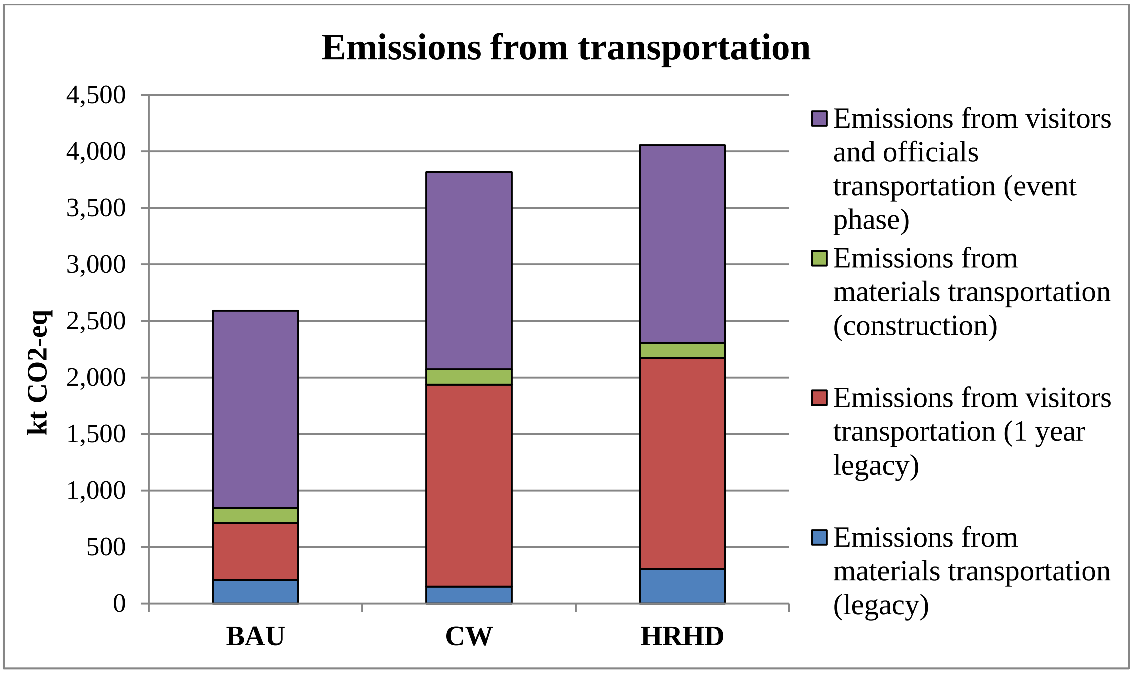


Figure 6. 9. Emissions from the transportation of construction materials and waste, visitors, officials and residents.

The total emissions resulting from the transportation are the highest for the HRHD scenario. Because the total emissions resulting from the construction and event phases are the same for each scenario, the highest emissions in the HRHD scenario can be explained by the larger amount of materials required for the construction of a post-event site (table 6.8) and by the higher estimated number of visitors to the post-event site. It was assumed that the number of visitors in the CW scenario will be the lowest; therefore, emissions associated with their transportation are also the lowest of all 3 scenarios. It was assumed that the sustainability constraint applied during the construction phase is also applied in the legacy phase which means that minimum 50% of all construction materials and waste has to be transported by rail and water. It was also assumed that most visitors, residents and employees would use rail to get to/from the site in the legacy phase due to the accessible public transport. Therefore, the capacity constraints for each transport modes were applied for all baseline scenarios based on the data provided in table 6.4. The results of the sensitivity analysis in section 6.5.2 illustrate how various changes regarding transport modes and distances travelled affect the total emissions.

6.5.2. Sensititivy analysis – transportation of materials and visitors.

Table 6.14 provides the data used for the sensitivity analysis to determine how changes in certain parameters affect the overall results.

Table 6. 14. Data used for the sensitivity analysis (transport).

	Original scenario	Sensitivity analysis - T1	Sensitivity analysis – T2
% of visitors using rail in London	75%	20%	75%
% of materials transported by rail	30%	10%	30%
distance travelled by a resident of a host city	24 km	24 km	48 km
distance travelled by a resident of a host country	330 km	330 km	430 km

Figure 6.10 provides the results of the sensitivity analysis for the Construction and Games phases; figures 6.11 – 6.13 demonstrate the results of the sensitivity analysis for the baseline scenarios of the post-event site.

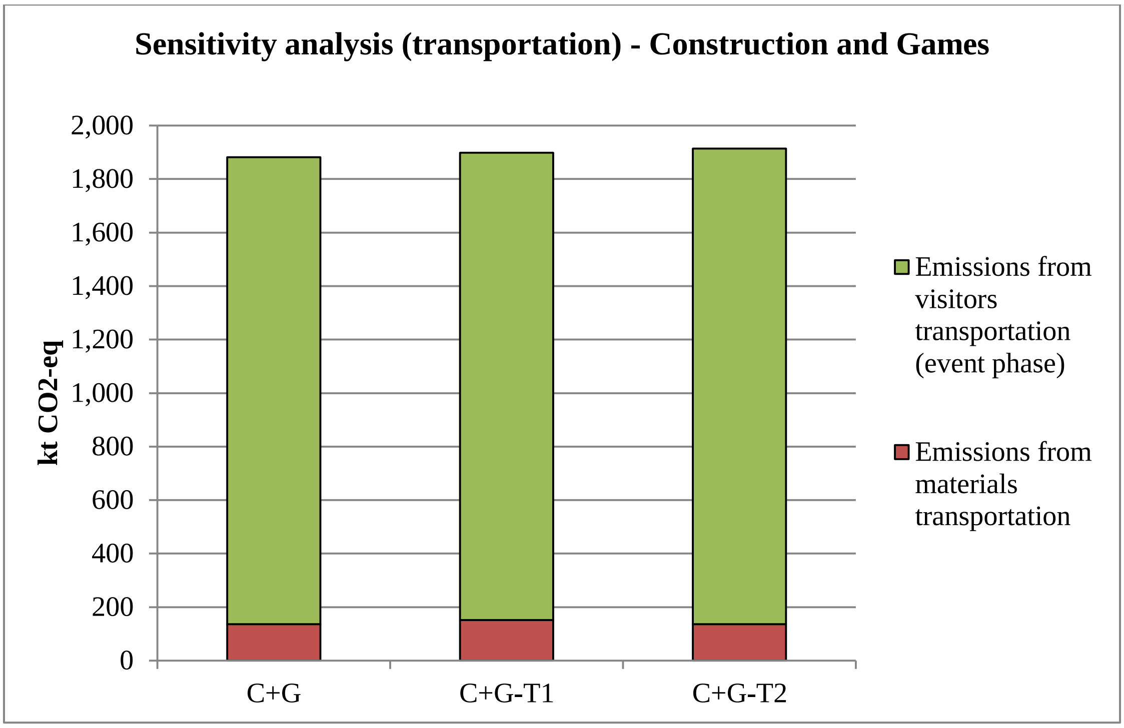


Figure 6. 10. Sensitivity analysis (transportation) – Construction and Games.

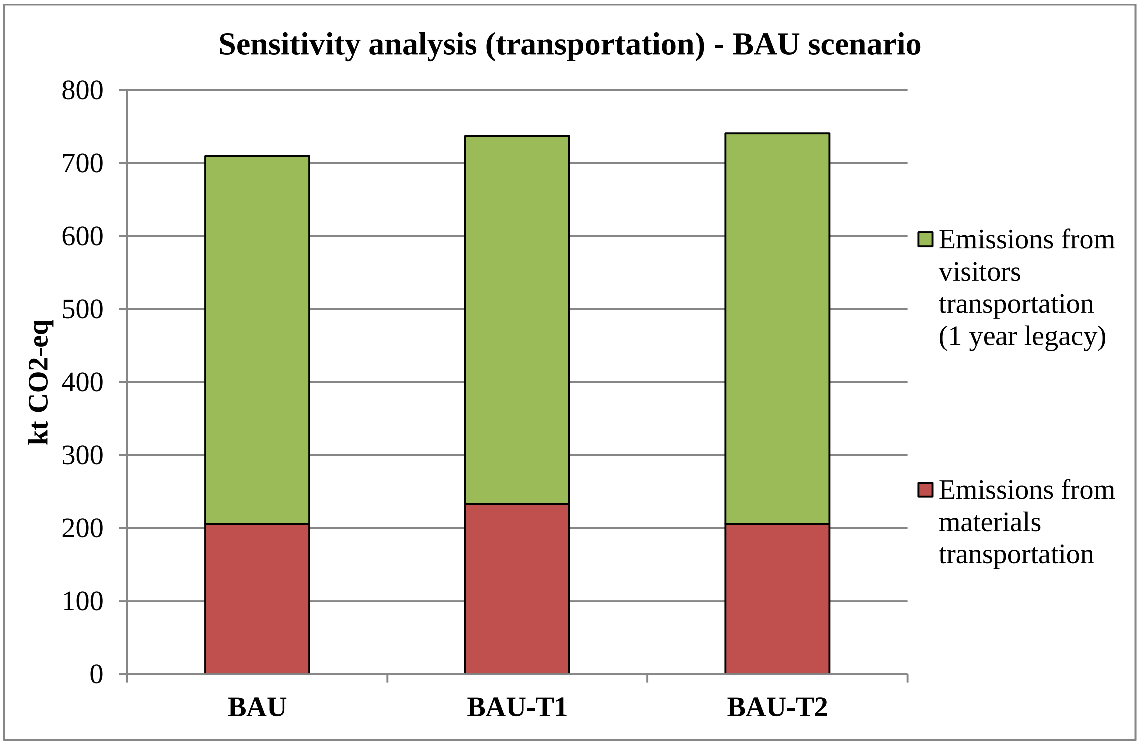


Figure 6. 11. Sensitivity analysis (transportation) – BAU scenario (1 year legacy period).

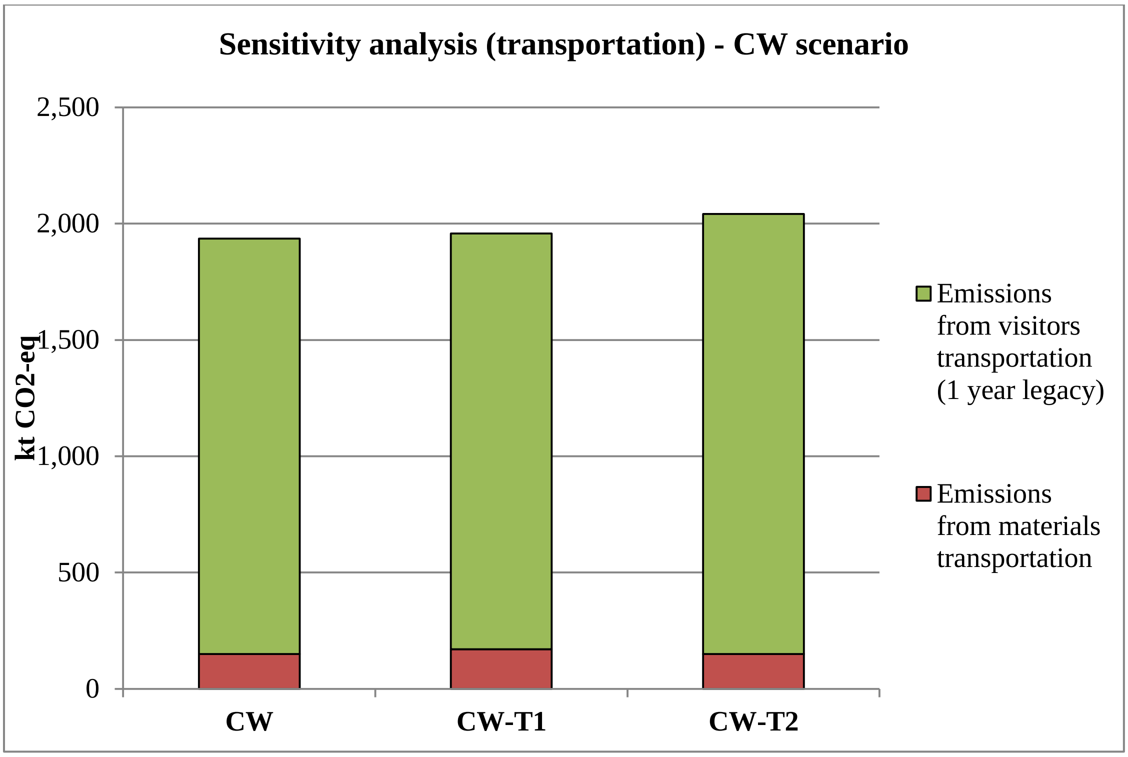


Figure 6. 12. Sensitivity analysis (transportation) – CW scenario (1 year legacy period).

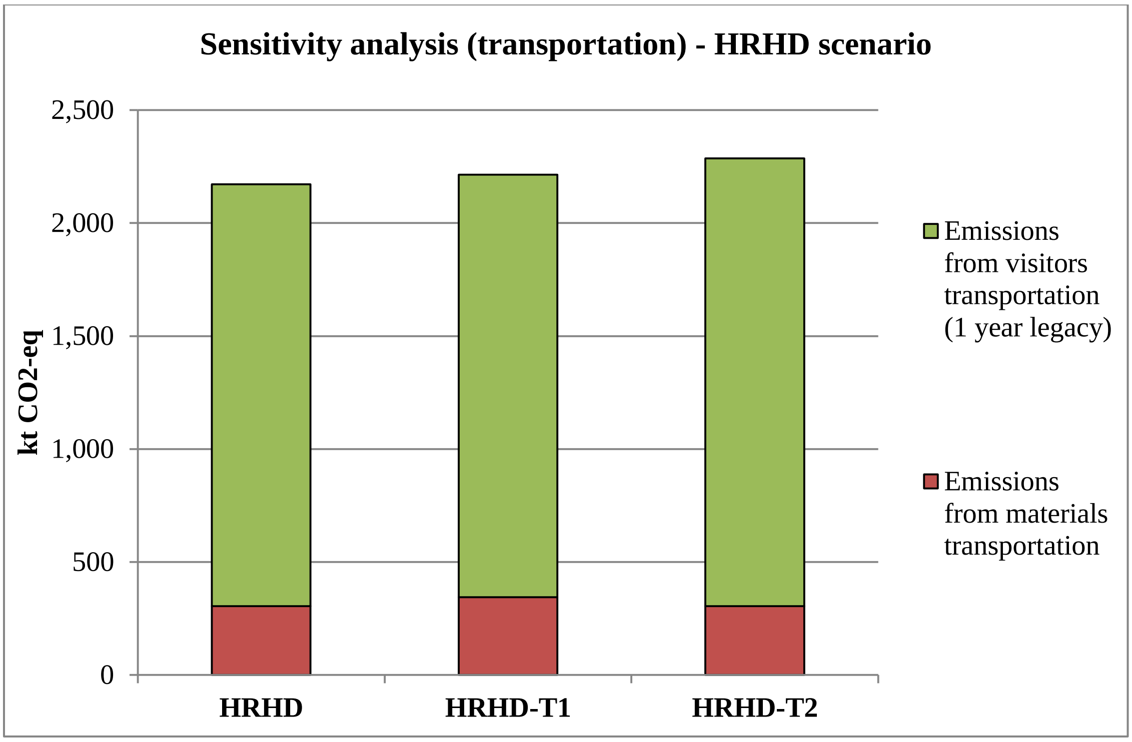


Figure 6. 13. Sensitivity analysis (transportation) – HRHD scenario (1 year legacy period).

It can be seen that changes in the transportation modes (scenario T1) have almost no effect on the overall results for the emissions from the transportation of visitors, however they result in higher emissions from materials transportation. This is due to the fact that in the baseline scenarios the amount of materials transported by rail was the same as the amount of materials transported by road (30%), the rest of materials (40%) transported by barges. In the sensitivity analysis T1, the amount of materials transported by rail was reduced to 10%, which increased the amount of materials transported by road to 70%. As a result, the total amount of emissions increases due to the higher emissions conversion factor for road transport (0.112 kg CO_2-eq/t.km) than the one for rail transport (0.063 kg CO_2-eq/t.km).

The results of a sensitivity analysis T2 show that the increase of distances travelled by residents of a host city and a host country results in increased emissions. For example, in the BAU scenario the emissions are increased by 5% with similar results for other scenarios.

In the next section the results for the emissions for the baseline scenarios are compared to the results for the optimum scenarios.

6.5.3. Baseline vs optimum scenarios – transportation.

Figure 6.14 shows the results for the transport emissions for baseline and optimum scenarios.

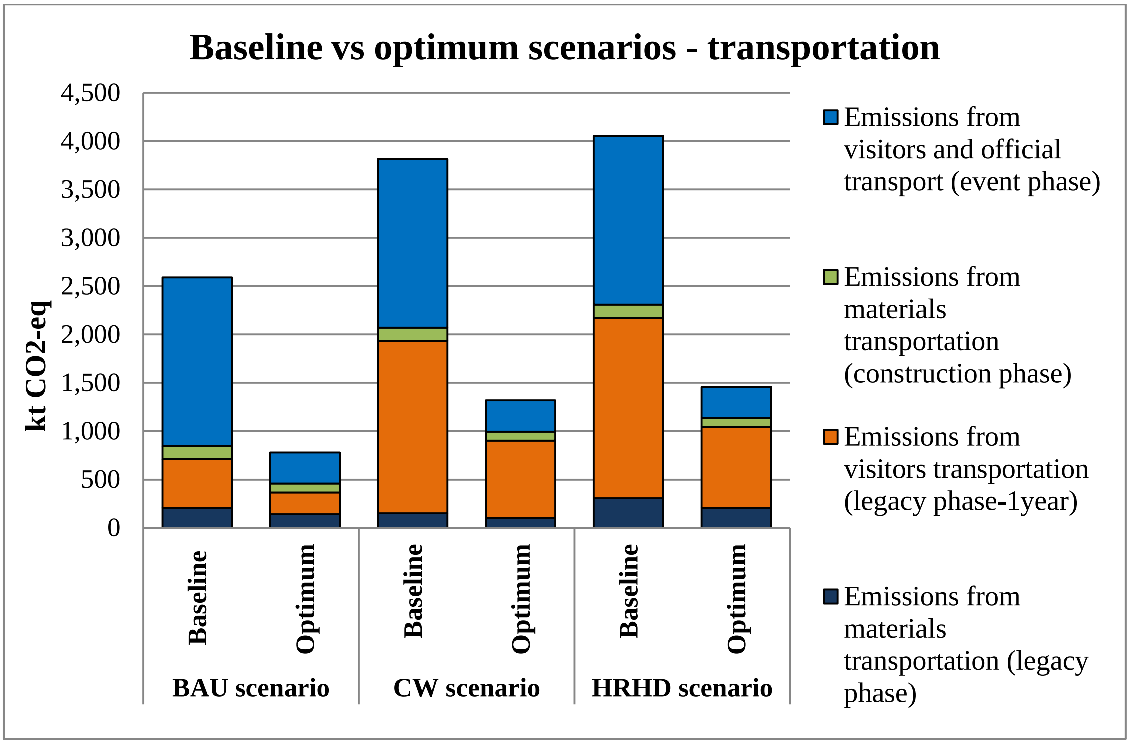


Figure 6. 14. GHG emissions from transportation – baseline vs optimum scenarios.

For the baseline scenarios, the emissions were calculated according to the constraints described in section 6.5.1. For the optimum scenarios, most of the constraints have been removed and the emissions were calculated assuming that the capacities of each transport mode will be sufficient for the transportation of all visitors and materials. For example, the results for the optimum scenarios 'force' all visitors from the RoW to fly economy class, all UK visitors to get to London by coach and all visitors from the EU to use Eurostar high speed train (see Appendix 3). Although the optimum scenarios can be considered the best option in terms of the overall emissions, they are quite unrealistic. First, there is a maximum capacity for each transport mode and, therefore, capacity constraints should be incorporated into modelling. Second, there is a human factor involved which means that people do not choose their preferred mode of transport only according to their environmental impacts. Therefore, for decision-making purposes it is necessary to base the assumptions and constraints on the real data.

6.6. Emissions from the use of energy and water.

6.6.1. Description of the model and results.

Increasing demand for the electricity, gas and oil is a great global challenge. It was estimated that the world energy demand will rise by 56% from 2010 to 2040, which in turn is expected to increase CO_2 emissions from 31.2 billion tonnes in 2010 to 45.5 billion tonnes in 2040 (USEIA, 2014). Additionally, fossil fuel reserves will deplete rapidly in the next decades (Iqbal et al., 2014). Thus, the governments, local authorities, industries and other policy makers are facing the challenge of adopting new strategies which focus on maximising energy efficiency and minimising CO_2 emissions.

In many countries access to clean water is also becoming more and more difficult due to the increasing population, industrialisation and climate change. Although up to 90% of the water withdrawn for domestic use is returned to rivers and aquifers as wastewater (Ertek and Yilmaz, 2014), both water and wastewater have to undergo treatment processes which consume energy and chemicals and, therefore, result in environmental burdens. Hence, policy makers face the challenge of developing sustainable water management strategies with the aim to reduce water consumption and emissions associated with water and wastewater treatment. This section presents the results of the estimated emissions resulting from the use of energy and water throughout the whole life cycle of a mega-event project for the baseline and optimum scenarios.

Problem statement:
The problem can be formulated as a single-objective optimisation problem as defined in the set of equations 6.1.

The objective is to minimise the total GHG emissions resulting from the use of energy and water (including removal and treatment of wastewater) during the construction of venues and infrastructure, staging of the event, and during the operation of a post-event site. The emissions are calculated based on the number and types of different buildings; total number of residents, visitors and employees; types of energy and fuels used and emissions conversion factors for electricity, fuels, water and wastewater treatment, subject to constraints.

Mathematical formulation.

The problem is formulated as a static, single-objective, linear programming (LP) model with the following categorisations:

Indices:

r	Residential buildings
c	Commercial and other non-residential buildings
o	Olympic Sports venues
v	Visitors' categories
n	New venues built on site during construction stage
s	Sectors of water and energy consumption and wastewater production

Sets:

R	Set of different types of residential buildings (1-, 2-, 3-bedroom house, 1-, 2-, 3-bedroom flat)
C	Set of different types of commercial and other non-residential buildings (office with/without canteen, office 1 – naturally ventilated cellular, office 2 – naturally ventilated open-plan, office 3 – air-conditioned standard, office 4 – air-conditioned prestige, restaurant 1 – large restaurant, restaurant 2 – medium restaurant, restaurant 3 – fast-food restaurant, medical centre, schools, hotels, community centres, supermarkets/retail stores).
O	Set of sports venues
V	Set of visitors' categories (general visitors and sports event visitors)

N Set of all new venues being built during the construction stage

S Set of different sectors and phases for water and energy consumption and wastewater production

Parameters:

W_r Daily water demand in different types of residential buildings (l dwelling^{-1})

W_c Daily water demand in different types of commercial and other non-residential buildings (l m^{-2})

W_o Daily water demand in various sports venues (l day^{-1})

W_v Water demand per each type of visitor. For sports events: spectators

(l hour^{-1}), competitors (l competitor^{-1} event^{-1}), staff (l day^{-1}). For general visitors water demand is expressed in l day^{-1}.

P_r Yearly electricity demand in all types of residential buildings

(kWh dwelling^{-1})

P_c Yearly electricity demand in all types of commercial and other non-residential buildings (kWh m^{-2})

P_o Daily electricity demand in all sports venues (kWh)

Q_r Yearly gas demand in all types of residential buildings

(kWh dwelling^{-1})

Q_c Yearly gas demand in all types of commercial and other non-residential buildings (kWh m^{-2})

Q_o Daily gas demand in all sports venues (kWh)

O_r Average occupancy of residents in different types of residential houses (person dwelling^{-1})

N_r Total number or residential units in all types of residential buildings

$R1$ Minimum amount of floor space required in schools per 1 pupil (m^2 pupil^{-1})

$R2$ Minimum amount of floor space required per patient in medical centres (m^2 patient $^{-1}$)

I_n Water demand for irrigation of different sites during the construction period (litres)

IG Daily water demand for irrigation of green spaces (l m^{-2})

AG Area of green space that requires irrigation (m^2)

NG Number of days a year when irrigation is required (days)

C_n Cost of each new venue during the construction (million £)

D_n Duration of construction of each new venue (month)

D_e Duration of the event (days)

$E1$ Emissions conversion factor for electricity (kg CO_2-eq kWh^{-1})

$E2$ Emissions conversion factor for gas (kg CO_2-eq kWh^{-1})

$E3$ Emissions conversion factor for potable water supply (kg CO_2-eq l^{-1})

$E4$ Emissions conversion factor for waste water treatment (kg CO_2-eq l^{-1})

$E5$ Emissions conversion factor associated with on-site diesel usage during the construction of new venues l (kg CO_2-eq million £ $^{-1}$)

T_v Daily visitors' dwelling time in each Olympic Sports venue (only applies to spectators) (hour day^{-1})

M_c Minimum floor area per each employee in the commercial offices (m^2 $employee^{-1}$)

Variables

N_c Number of each type of non-residential building

N_{vo} Number of each type of visitors (e.g. competitors, employees) in all sporting venues

A_c Total floor area of each type of the non-residential buildings (m^2)

TR Total number of residents in all residential buildings

TC Total number of employees in all commercial offices

A1 Total minimum required floor area of all schools

A2 Total minimum required floor area of all health centres

F_r Fractions of different types of residential buildings in regards to the total number of residential units

EW_o Total GHG emissions from water use in sports venues

EW_r Total GHG emissions from water use in residential buildings

EW_c Total GHG emissions from water use in commercial buildings

EWi Total GHG emissions from water use for irrigation purposes

EE_o Total GHG emissions from energy use in sports venues

EE_r Total GHG emissions from energy use in residential buildings

EE_c Total GHG emissions from energy use in commercial buildings

EE_n Total GHG emissions from energy use for irrigation purposes

EWE Total GHG emissions from energy and water use in all buildings

Z_w Total amount of waste produced on site

Constraints

- ***Residents' constraint***

Total number of residents on site in the post-event phase depends on the number and type of various residential dwellings and resident's occupancy in each type of dwelling. Total number of residents is estimated as follows:

$$TR \leq \sum_{r \in R} O_r \, F_r \, N_r \tag{6.12}$$

where N_r is the total number of residential units, O_r is the resident's occupancy in each type of residential building, F_r fractions of each type of residential building.

- ***Employees' constraint***

Total number of employees in commercial offices depends on the total area of all offices and the office floor area required per employee. The floor area per employee will vary significantly depending on the type of the office, nature of business and other factors. The number of employees in commercial offices is estimated as follows:

$$TC \leq \sum_{c \in C} A_c \, M_c \tag{6.13}$$

where A_c is the total floor area of all commercial offices, M_c is the minimum floor area per employee. The floor area per employee varies significantly depending on the office type and according to the workplace regulations should not be less than 4 m^2 (HSE, 1992). In this work it is assumed that the average floor area per employee (M_c) is 15 m^2.

- ***Residential building types constraints***

The total number of the residential buildings in the post-event site varies significantly depending on the design scenario. Residential buildings also vary in type: from 3-bedroom detached house to 1-bedroom apartment. F_r is the fraction of each type of the residential building represented as a percentage of the total number of the residential buildings. Thus, the sum of all fractions is equal to 1. Therefore:

$$\sum_{r \in R} F_r = 1 \qquad \forall r \in R \qquad (6.14)$$

where F_r is the fraction of each type of residential buildings.

- ***Building regulations constraints***

According to the Census 2011 published by the UK Office for National Statistics (OfNS, 2012), the age group of children 0-19 years old is approximately 24%. Therefore, assume that number of children attending schools and nurseries will be 20% of the total population in the area. Schools vary in size depending on the number of pupils and types of various facilities such as music rooms, laboratories, teaching rooms, etc. Thus, the total floor area and the average area per pupil may vary significantly. Based on the Building Bulletin 103 (DfE, 2014), assume that an average required floor area per pupil (*R1*) is 7.85 m^2. The outside area is not considered in this work. Therefore, the minimum floor area required for schools can be determined as follows:

$$A1 \geq TR \times R1 \times 0.2 \qquad (6.15)$$

where *A1* is the total minimum floor area of all schools (m^2), *TR* is the total number of residents on site, *R1* is the minimum floor area required per pupil (m^2 pupil^{-1}).

Building regulations provide guidance on the minimum floor area required per user of a certain building. The minimum floor areas for medical centres and schools are calculated based on the estimated number of pupils in schools and patients in the medical centres and the minimum required space per patient and per pupil. According to the UK standards for medical and dental centres (JSP, 2013), a minimum required area per patient (*R2*) is 0.5 m^2. Assume that the maximum average daily number of patients attending medical centres will be 3% of the total population in the area. Therefore, the minimum floor area required for medical centres can be determined as follows:

$$A2 \geq TR \times R2 \times 0.03 \qquad (6.16)$$

where $A2$ is the total minimum floor area of all medical centres, TR is the total number of residents on site, $R2$ is the minimum floor area required per patient (m^2 $patient^{-1}$).

Objective function

The objective function is based on the minimisation of the total GHG emissions resulting from the supply of energy and water and removal of wastewater from all buildings on site during the construction, staging of the event and operation of the post-event site and is formulated as follows:

Minimise EWE

s.t. Building type's constraint

Building regulations' constraint

Employees' and residents' constraints

The total emissions resulting from the energy and water use are calculated by:

$$EWE = \sum_{s \in S} EE_s + \sum_{s \in S} EW_s \qquad (6.17)$$

where EE_s is the GHG emissions resulting from use of energy in each sector s, EW_s is the GHG emissions resulting from the use of water (including wastewater treatment) in each sector s. Sectors s include emissions from the use of energy during the construction phase, use of energy during the staging of the event and from the use of energy in the residential, commercial and other buildings in the post-event phase.

Emissions resulting from energy use in each sector are calculated as follows:

- Emissions from the energy use in sports venues:

$$EE_o = \sum_{o \in O} P_o \, E1 \, D_e + \sum_{o \in O} Q_o \, E2 \, D_e \qquad (6.18)$$

where P_o is the daily electricity demand in all sports venues (kWh), Q_o is the daily gas demand for each type of sports venue (kWh), *E1* -emissions conversion factor for electricity (kg CO_2-eq kWh^{-1}), *E2*- emissions conversion factor for gas (kg CO_2-eq kWh^{-1}), D_e – duration of the event (days).

- Emissions from the energy use in the residential buildings:

$$EEr = \sum_{r \in R} P_r \, E1 + \sum_{r \in R} Q_r \, E2 \tag{6.19}$$

where P_r is the annual electricity demand for each type of residential building (kWh), Q_r is the annual gas demand for each type of residential building (kWh), *E1* - emissions conversion factor for electricity (kg CO_2-eq kWh^{-1}), *E2*- emissions conversion factor for gas (kg CO_2-eq kWh^{-1})

- Emissions from the energy use in the non-residential buildings:

$$EEc = \sum_{c \in C} P_c \, E1 + \sum_{c \in C} Q_c \, E2 \tag{6.20}$$

where P_c is the annual electricity demand for each type of non-residential building (kWh), Q_c is the annual gas demand for each type of non-residential building (kWh), *E1* is the emissions conversion factor for electricity (kg CO_2-eq kWh^{-1}), *E2* is the emissions conversion factor for gas (kg CO_2-eq kWh^{-1})

- Emissions from the energy use during the construction phase:

Emissions from on-site diesel use during construction were calculated based on the methodology developed by London2012 (2007b). Emissions were estimated based on the assumption of 1.575 tCO_2 per £millions of construction cost multiplied by the number of months on site.

$$EE_n = \sum_{n \in N} C_n D_n \, E5 \tag{6.21}$$

where C_n is the cost of each new venue during the construction (million £), D_n is the duration of construction of each new venue (month), *E5* is the emissions conversion factor for diesel (kg CO_2-eq million £ $^{-1}$).

Emissions resulting from water use in each sector are calculated as follows:

- Emissions from water use in sports venues:

$$EWo = \sum_{o \in O} \sum_{v \in V} N_{vo} W_o T_v (E3 + E4) \qquad (6.22)$$

where N_{vo} is the number of all types of visitors in all sporting venues, W_o is the daily water demand in various sports venues (l day^{-1}), T_v is the daily visitors' dwelling time in each sports venue (only applies to spectators) (hour day^{-1}), *E3* is the emissions conversion factor for potable water input supply (kg CO_2-eq l^{-1}), *E4* is the emissions conversion factor for waste water output treatment (kg CO_2-eq l^{-1})

- Emissions from water use in residential buildings:

$$EW_r = 365 \sum_{r \in R} N_r F_r W_r (E3 + E4) \qquad (6.23)$$

where N_r is the total number of the residential units, F_r are the fractions of different types of residential buildings in regards to the total number of residential units, W_r is the daily water demand in residential buildings, *E3* is the emissions conversion factor for potable water input supply (kg CO_2-eq l^{-1}), *E4* is the emissions conversion factor for waste water output treatment (kg CO_2-eq l^{-1}), 365 is the number of days of water use in residential buildings per year.

- Emissions from water use in non-residential buildings:

$$EW_c = 250 \sum_{c \in C} A_c W_c (E3 + E4) \qquad (6.24)$$

where A_c is the floor area of each type of non-residential buildings, W_c is the daily water demand in different types of non-residential buildings, *E3* is the emissions conversion factor for potable water input supply (kg CO_2-eq l^{-1}), *E4* is the emissions conversion factor for waste water output treatment (kg CO_2-eq l^{-1}), 250 is the average number of working days per year.

- Emissions from water use for irrigation purposes:

$$EW_i = (AG \times IG \times NG + I_n) \times E3 \qquad (6.25)$$

where *AG* is the area of green space that requires irrigation (l m^{-2}), *NG* is the number of days a year when irrigation is required (days), *IG* is the daily water demand for irrigation of green spaces (m^2 day^{-1}), In is the amount of water required for other irrigation purposes (for example, during the construction phase), *E3* is the emissions conversion factor for potable water input supply (kg CO_2-eq l^{-1}).

As mentioned earlier, the emissions resulting from the treatment of MSW are calculated in chapter 7. The total amount of MSW depends on the amount and composition of MSW produced in various types of buildings and can be estimated as follows:

$$Z_w = Z_o + Z_r + Z_c \qquad (6.26)$$

where Z_o is the amount of MSW produced annually in venues during the event and in the post-event phase (t), Z_r is the amount of MSW produced annually in residential buildings (t), Z_c is the amount of MSW produced annually in various types of non-residential buildings (t). The composition and amount of waste generated annually in different buildings varies significantly. The data on waste for each building is provided in Appendix 1.

Computational results.

The results in table 6.15 provide information on the amounts of energy and water used during the construction of the event site and during the staging of the event. The results in tables 6.18 - 6.20 provide information on the estimated amounts of energy and water required for the operation of buildings on site in the legacy phase.

Table 6. 15. Total energy and water demand during the construction and the event phases.

	Total energy demand				**Total water demand**
	Electricity (MWh)	**Gas (MWh)**	**Diesel (l)**	**Propane mix (m^3)**	**Water(Ml)**
Sports venues	19,150	8,511			551,824
Olympic Village	4,300	1,932			60,305
Media and Broadcast Centre	6,250	3,125			145,853
Torch relay				0.26	
Irrigation + other water use					1,753,910
Construction			35,445		173,835
Other energy use	112				
Total	**29,812**	**13,568**	**35,445**	**0.26**	**2,685,729**

It is clear that the highest amount of energy use is associated with the use of diesel during the construction phase followed by the use of electricity in the Olympic sports venues during the event. The highest water demand occurs during the irrigation of green spaces and water supply for the sports event during the event.

Table 6.16 presents the results for the GHG emissions arising from the use of energy and water during the construction of the event venues and infrastructure and during the staging of the event.

Table 6. 16. Total GHG emissions associated with energy and water use during the construction of the site and staging of the event.

	GHG emissions (t CO_2-eq) resulting from the usage of:				
	Electricity	**Gas**	**Diesel**	**Propane mix**	**Water**
Sports venues	8,618	1,532			621
Olympic Village	1,935	348			68
Media and Broadcast Centre	2,813	562			164
Torch relay				0.067	
Irrigation + other water use					1,937
Construction phase			92,157		196
Other energy use	51				
Total	**13,416**	**2,442**	**92,157**	**0.067**	**3,021**

The total GHG emissions resulting from the use of energy and water during the construction of the site and staging of the event is 111 kt CO_2-eq. It can be seen that the largest part of the emissions is attributed to the use of diesel during the construction phase (83%). Although more than 3 Tl of water was used during the construction and staging of the event, GHG emissions resulting from potable water supply and waste water removal account for less than 20% of the total emissions associated with supply of the electricity and gas during the event. This is due to the low values of emissions coefficients for water supply and wastewater treatment compared to those for electricity and gas supply.

Tables 6.18 – 6.20 provide the results of the estimated amount of energy and water used during 1 year of the operation of a post-event site for the baseline legacy design scenarios.

It can be seen that the annual emissions from the energy and water use in the BAU scenario are the lowest of all scenarios. This is due to a smaller number of residents compared to the HRHD scenario and much smaller number of employees in commercial offices compared to the CW scenario. The data on the number of residents and employees for the baseline legacy scenarios is provided in table 6.17.

Table 6. 17. Estimated number of residents and employees for each baseline legacy scenario.

Baseline legacy scenario	Number of residents	Number of office employees
BAU scenario	18,182	5,515
CW scenario	6,308	170,860
HRHD scenario	32,900	88,220

Table 6. 18. Total annual energy and water demand and GHG emissions for the BAU baseline scenario.

	Total annual demand			**Total GHG annual emissions (t CO_2-eq)**		
	Electricity (MWh)	**Gas (MWh)**	**Water (Ml)**	**Electricity**	**Gas**	**Water**
Sports venues	31,523	22,353	78	14,200	4,024	88
Residential buildings	28,579	100,637	621	12,861	18,115	698
Office buildings	30,500	24,430	113	13,700	4,389	127
Restaurants	14,442	33,698	8	6,499	6,066	5
Supermarkets/retail	33,885	5,648	5	15,248	1,017	46
Community centres	93	260	1	42	17	1
Medical centres	120	412	3	54	22	3
Schools/nurseries	1,150	3,134	30	517	207	34
Hotels	2,520	2,688	920	1,134	484	1,035
Irrigation + other use			157			54
Total	**142,812**	**193,259**	**1,936**	**64,255**	**34,339**	**2,092**

Table 6. 19. Total annual energy and water demand and GHG emissions for the CW baseline scenario.

	Total annual demand			Total GHG annual emissions (t CO_2-eq)		
	Electricity (MWh)	**Gas (MWh)**	**Water (Ml)**	**Electricity**	**Gas**	**Water**
Sports venues	31,523	22,353	78	14,185	4,024	88
Residential buildings	9,804	31,996	273	4,412	5,759	307
Office buildings	807,561	737,300	3,393	363,403	132,714	3,818
Restaurants	8,022	18,718	3	3,610	3,369	3
Supermarkets/retail	56,475	9,413	69	25,414	1,694	77
Community centres	46	130	1	21	8	1
Medical centres	42	143	1	19	7	1
Schools/nurseries	399	1,087	11	180	72	12
Hotels	13,272	14,784	933	5,972	2,661	1,050
Irrigation + other use			157			54
Total	**927,144**	**835,924**	**4,919**	**417,215**	**150,309**	**5,410**

Table 6. 20. Total annual energy and water demand and GHG emissions for the HRHD baseline scenario.

	Total annual demand			Total GHG annual emissions (t CO_2-eq)		
	Electricity (MWh)	**Gas (MWh)**	**Water (Ml)**	**Electricity**	**Gas**	**Water**
Sports venues	31,523	22,353	78	14,185	4,024	88
Residential buildings	50,008	160,552	1,352	22,504	28,899	1,521
Office buildings	778,034	461,597	1,818	350,115	83,087	2,045
Restaurants	13,426	31,327	369	6,042	5,639	415
Supermarkets/retail	169,425	28,238	206	76,241	5,083	232
Community centres	325	909	5	146	59	5
Medical centres	217	745	5	98	39	5
Schools/nurseries	2,081	5,671	55	936	375	62
Hotels	26,880	30,240	1,226	12,096	5,443	38
Irrigation + other use	0	0	157	0	0	54
Total	**1,071,919**	**741,631**	**5,272**	**482,363**	**132,647**	**4,465**

Figure 6.15 provides the overall results for the emissions for 3 baseline legacy scenarios. It is obvious that the lowest emissions occur in the BAU scenario. This is due to the lowest amount of new commercial offices compared to the other scenarios and lower number of residents compared to the HRHD scenario. Therefore, the majority of electricity and gas usage is attributed to the office buildings (tables 6.17 – 6.19). It can be seen that although the total annual demand for electricity in the CW and HRHD scenarios is only 10% and 20% higher than the total annual gas demand, the emissions from the electricity account for approximately 73% and 70% for the CW and HRHD scenarios respectively. This is due to the lower emissions conversion factor for 1 kWh of the UK grid gas compared to the emissions conversion factor for the UK grid electricity mix. It can also be seen that the emissions resulting from

water supply contribute to less than 1% of the total emissions for all baseline legacy scenarios.

In the section 6.6.2 the results of the sensitivity analysis are provided which identify how changes of certain parameters affect the overall results.

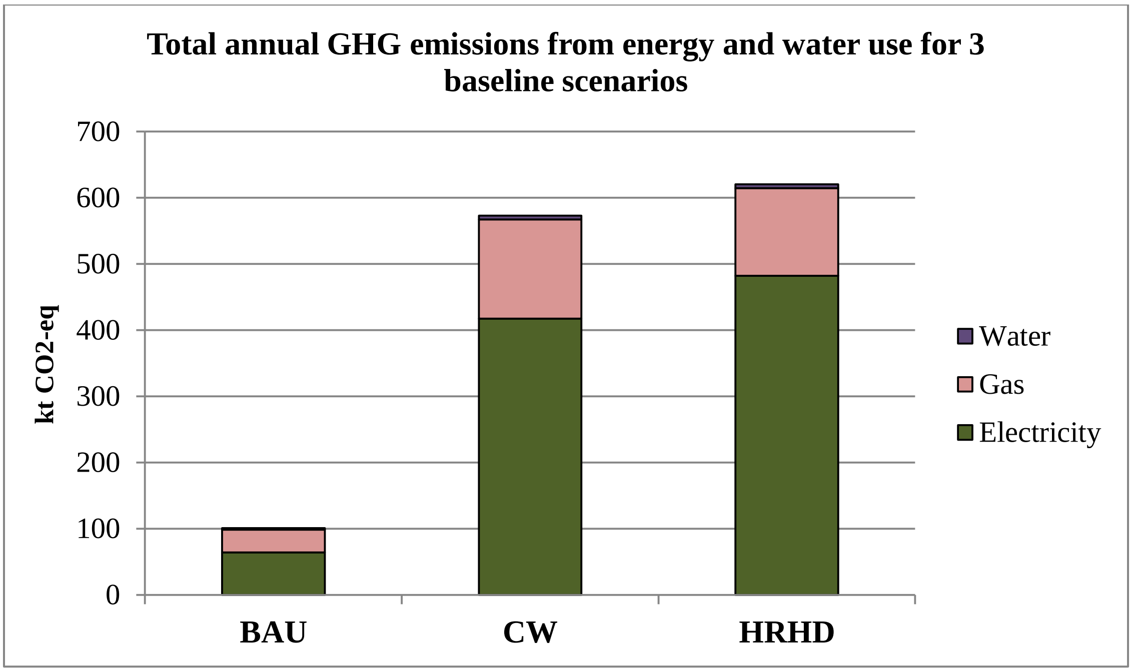


Figure 6. 15. Estimated total annual GHG emissions associated with the use of energy and water for 3 baseline legacy scenarios.

6.6.2. Sensitivity analysis – energy and water use.

From figure 6.15 it is evident that the majority of emissions resulting from the energy and water use arise from the electricity in all three post-event scenarios and the lowest emissions are attributed to water and wastewater. Therefore, it is evident that the changes associated with electricity, such as the amount of electricity used and electricity mix will have the greatest impact on the overall results.

In all models, the average UK grid electricity emissions conversion factor is assumed to be 0.45 kg CO_2-eq/kWh (DEFRA, 2014). Emissions conversion factor for the electricity is the measurement of the amount of carbon dioxide that results from the generation of 1 kWh of electricity. The value of the electricity emissions conversion factor may vary significantly between different countries and depends on many aspects such as the source of the electricity (geographical location) and the amount of low-carbon or renewable energy. In the UK, emissions factors are published yearly by the Department of Energy and Climate Change (DECC). The results of the sensitivity analyses E1 and E2 demonstrate how changes of the emissions conversion factor affect the overall results associated with energy and water use in buildings. The emissions conversion factors used in the sensitivity analyses are presented in table 6.21.

Table 6. 21. Data on changes of emissions conversion factor for 1 kWh of electricity used in the sensitivity analyses E1 and E2.

	Original scenario	**Sensitivity analysis – E1**	**Sensitivity analysis – E2**
Emissions conversion factor for the UK electricity grid mix (kg CO_2-eq/kWh)	0.45	0.4	0.5

From figures 6.16 – 6.18 it is obvious that by reducing the value of the emissions conversion factor for the UK grid electricity mix by 0.05 kg CO_2-eq/kWh compared to the current value will reduce the emissions associated with the electricity use by approximately 11% in all 3 scenarios. If the UK grid electricity mix changes so that the value of the electricity emissions coefficient is increased by 0.05 kg CO_2-eq/kWh, then the total emissions associated with the electricity use increase by approximately 11% in all 3 scenarios.

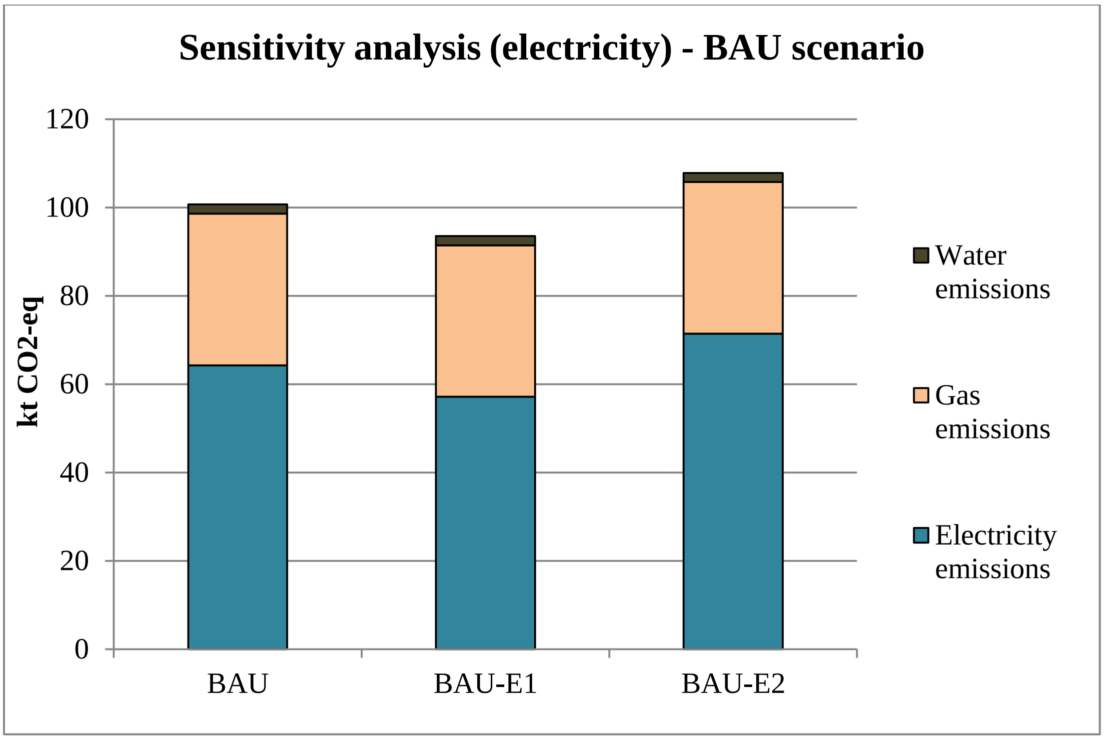


Figure 6. 16. Sensitivity analysis (changes in electricity emissions factor) – BAU scenario.

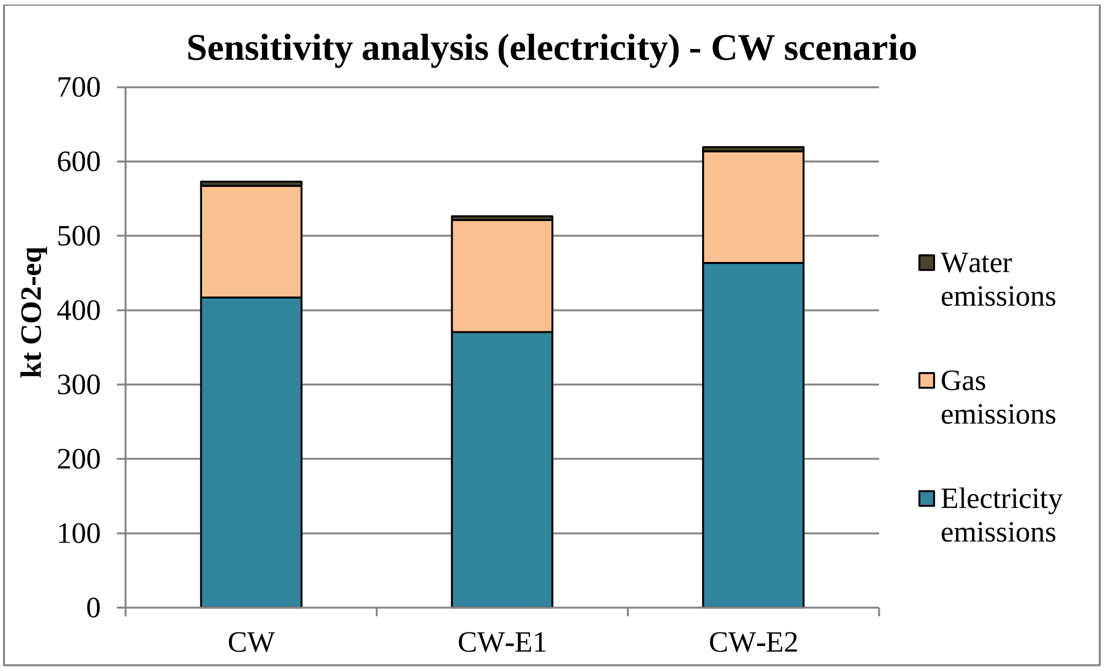


Figure 6. 17. Sensitivity analysis (changes in electricity emissions factor) – CW scenario.

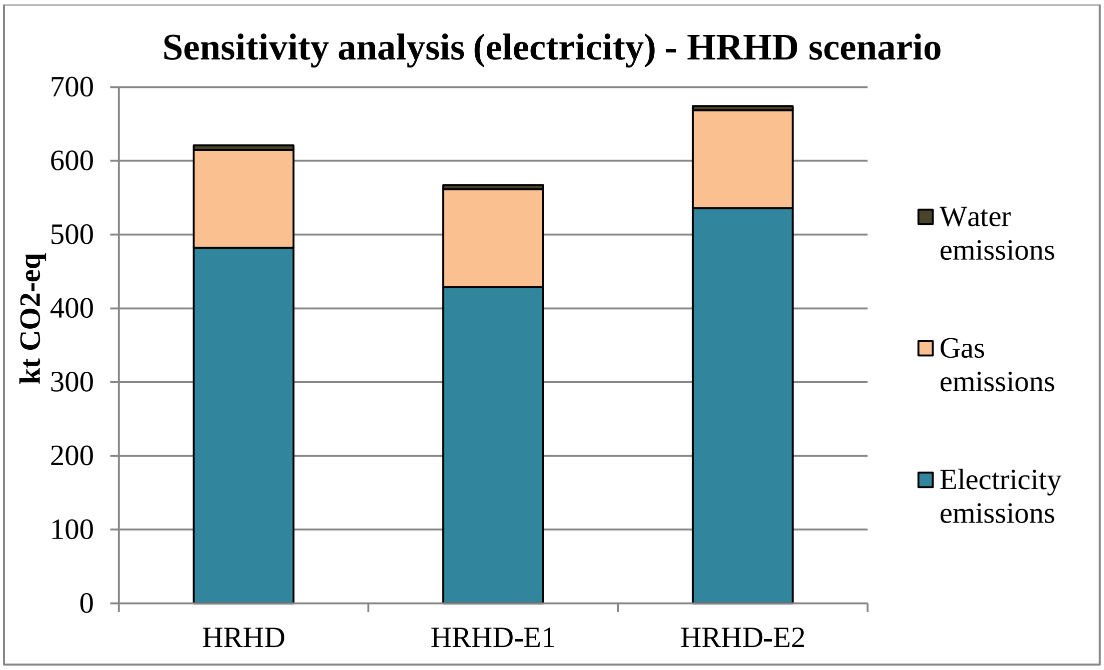


Figure 6. 18. Sensitivity analysis (changes in electricity emissions factor) – HRHD scenario.

Section 6.6.3 provides the results for the emissions from energy and water use for the baseline and optimum scenarios.

6.6.3. Baseline vs optimum scenarios – energy and water use.

The results presented in table 6.19 demonstrate how the total emissions resulting from the use of energy and water for the post-event baseline scenarios vary from the optimised scenarios. The objective function is to minimise the emissions resulting from the use of energy and water during the first year of the legacy period. In the baseline scenarios, the constraints were introduced for the minimum and maximum number of different types of the residential buildings and for the minimum and maximum floor area for each type of the commercial offices (see Appendix 2). In the optimum scenarios, all constraints were removed. As a result, in the optimum scenarios all types of residential dwellings are 'forced' to become 1 bedroom flats and all offices and other types of non-residential buildings are 'forced' to become 'Office type 1' which requires the least amount of energy and water use per 1 m^2 compared to other types of non-residential buildings (see Appendix 3). As mentioned earlier, the optimum scenarios are quite unrealistic because not all residential dwellings will be 1 bedroom flats and not all non-residential buildings will be of the office type with the least energy and water consumption. However, the models can be used as a tool to evaluate various alternatives and determine how changes in certain variables and constraints can affect the overall results.

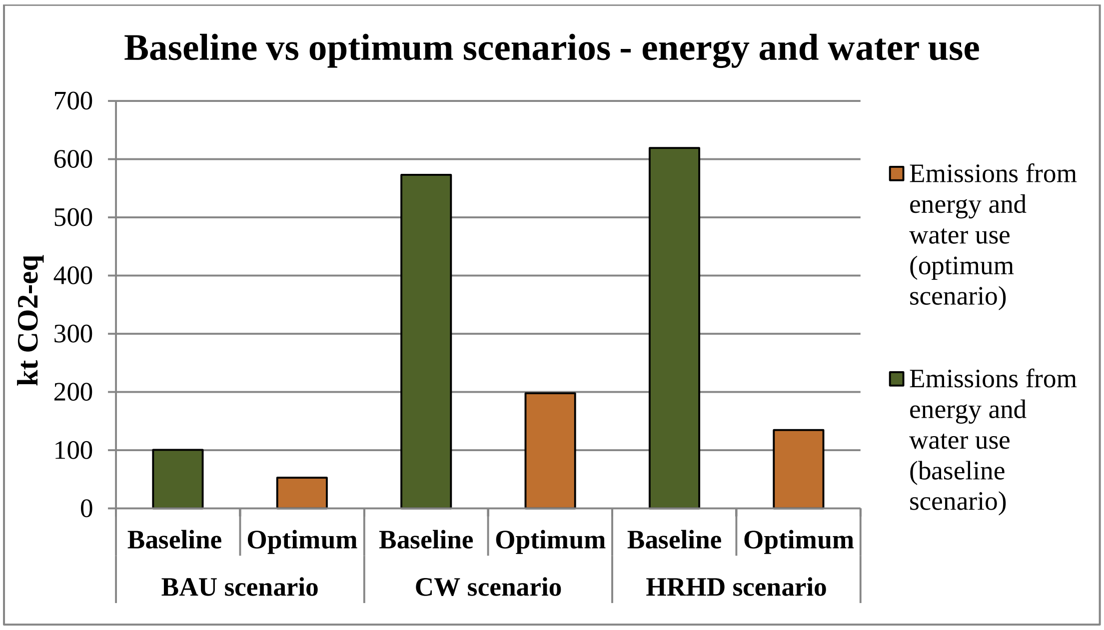


Figure 6. 19. GHG emissions from the energy and water in the legacy phase – baseline vs optimum scenario.

6.7. Overall results for all scenarios.

6.7.1. Results for the whole project's life cycle for 3 baseline scenarios.

Figures 6.20 – 6.22 present the overall results of the estimated emissions resulting from the whole life cycle of a mega-event project for 3 baseline scenarios. The objective function is to minimise the overall emissions resulting from the construction, the event and the total duration of the legacy phase. The legacy phase in this work is assumed to be 25 years.

From the figures 6.20 – 6.22 it is clear that in all baseline scenarios the highest emissions occur in the legacy phase. In the BAU and HRHD scenarios, the embodied emissions from the construction materials used for the redevelopment of the post-event site account for almost half of the total emissions of a project's life cycle followed by the emissions from the transportation of visitors, residents and employees in the legacy phase.

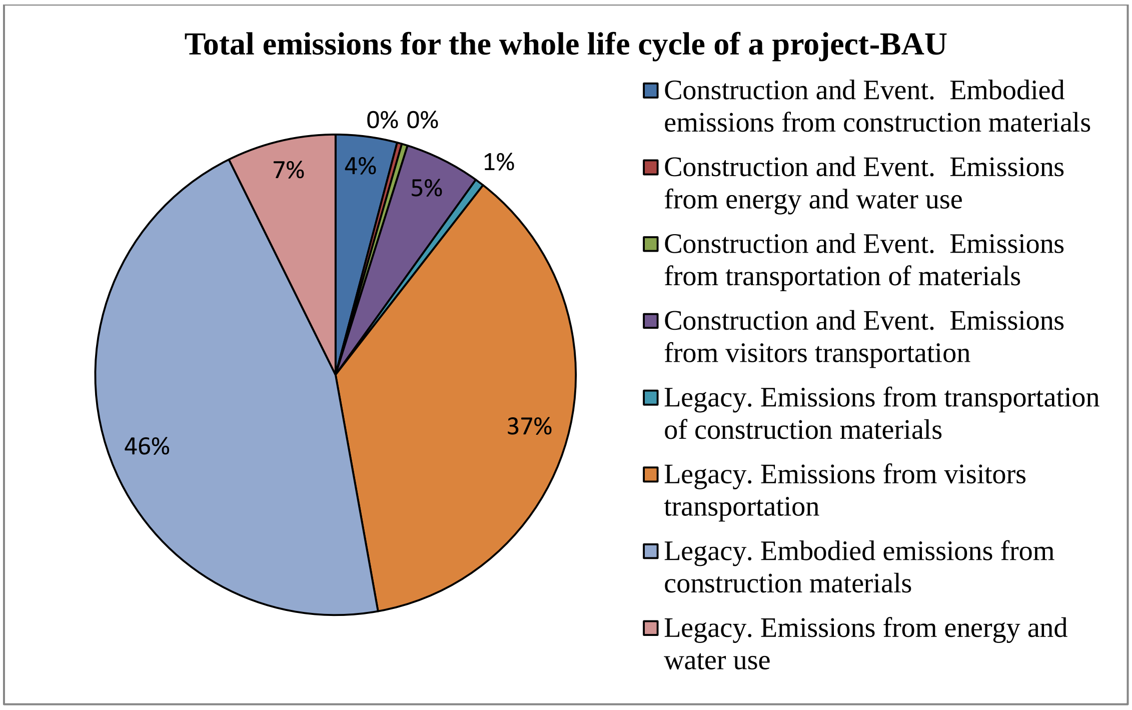


Figure 6. 20. Total emission for the whole life cycle of a mega-event project – BAU scenario.

In the CW scenario the highest emissions occur from the transportation of visitors, residents and employees followed by the embodied emissions from construction materials used in the legacy phase during the post-event site redevelopment.

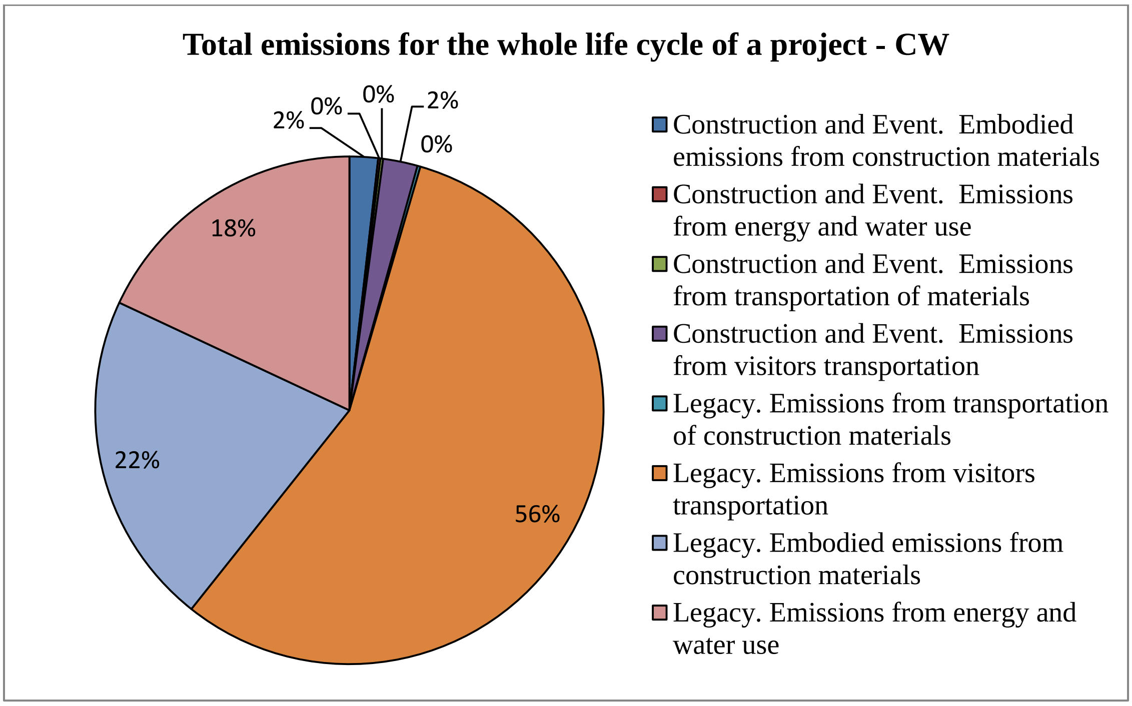


Figure 6. 21. Total emission for the whole life cycle of a mega-event project – CW scenario.

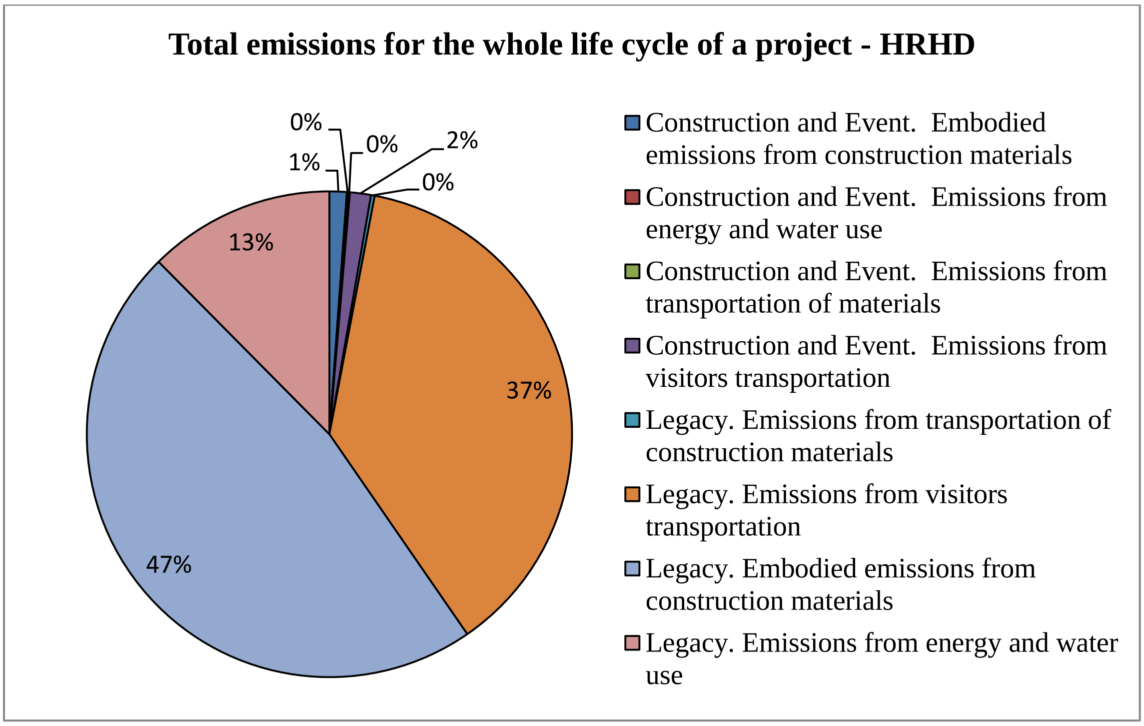


Figure 6. 22. Total emission for the whole life cycle of a mega-event project – HRHD scenario.

The results of the models emphasise the fact that the environmental impacts associated with the actual event are almost negligible compared to those associated with the legacy phase. Therefore, although it is important to minimise the environmental burdens resulting from the construction of the event infrastructure and staging of the event, it is the legacy phase that deserves a particular attention because most of the emissions occur during the redevelopment of the post-event site and operation of the infrastructure in the legacy phase.

6.7.2. Results for the whole project's life cycle: baseline vs optimum scenarios.

Figure 6.23 presents the results of the total emissions for the whole project's life cycle for the baseline and optimum scenarios. It can be noted that the highest emissions result from the HRHD scenario and the lowest from the BAU scenario.

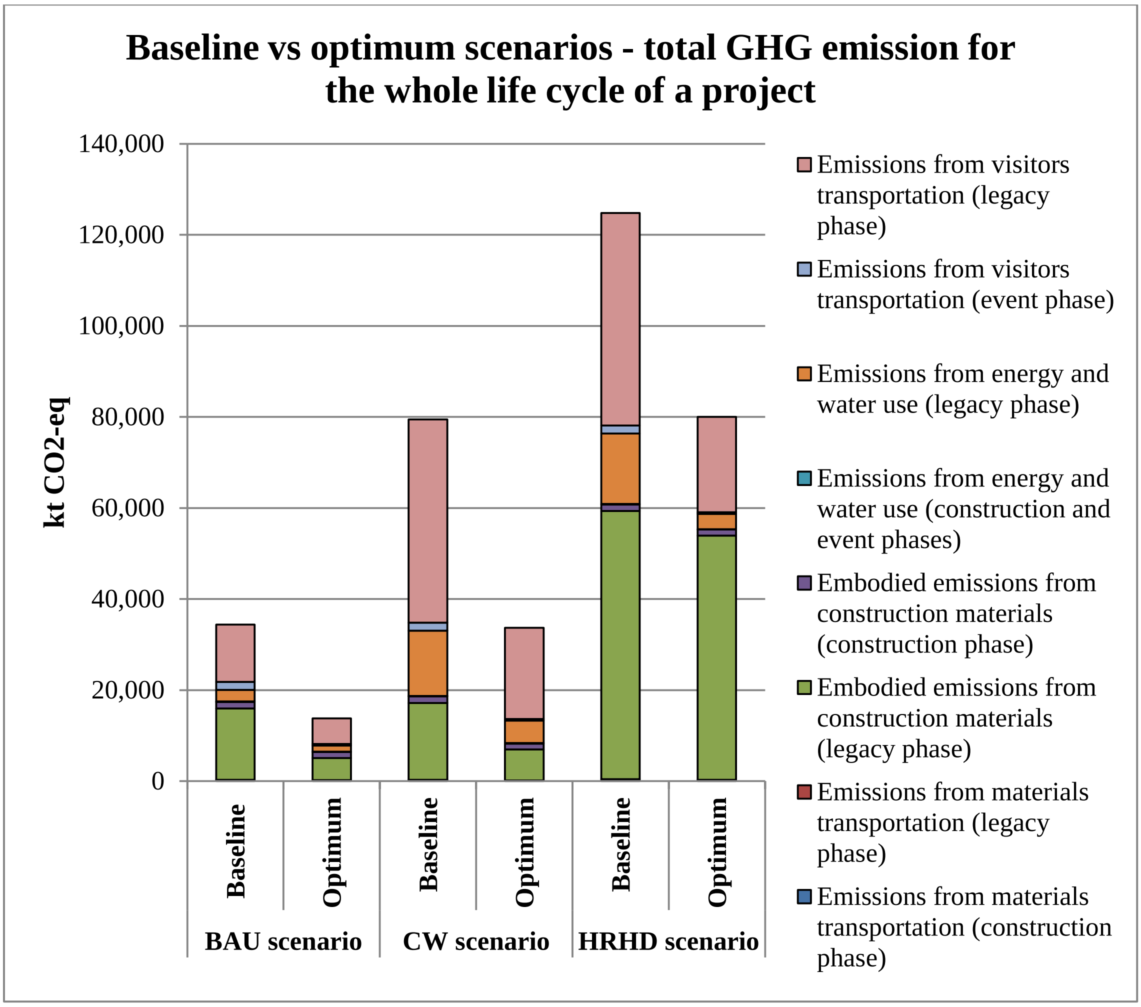


Figure 6. 23. Total GHG emissions for the whole life cycle of the project – baseline vs optimum scenarios.

In the optimum BAU and CW scenarios the total amount of emissions is reduced by approximately 40% compared to the baseline scenario and in the optimum HRHD scenario the total amount of emissions is reduced by just over 30%. As was discussed earlier, the highest emissions reduction can be achieved in the legacy phase mainly due to the changes in the transportation modes and due to the substitution of some virgin building materials with the recycled ones.

6.8. Discussion of results.

Section 6.7 presented the results of the total environmental impacts of the three proposed design scenarios for the whole project's life cycle. The results for the baseline scenarios were estimated based on the data provided in section 6.3 which specifies a number of design constraints such as the number and types of residential dwellings and office buildings, visitors' transportation mode, etc. The results for the optimum scenarios were estimated when most of the constraints have been removed. Hence, they present theoretical optimal solutions in terms of the minimum environmental impacts that could be achieved.

The optimum solution, however, may not be the final solution agreed on by the majority of key stakeholders during the planning process. Investors or architects may insist on a specific building design despite the fact that it might result in higher environmental impacts than the optimum solution. Project managers may choose not to use the environmentally optimum transportation mode for the materials or not to purchase the recycled building materials due to the high economic costs. Social factors also play a significant role. For example, the majority of the potential residents may prefer to live in a semi-detached house; therefore, the decision makers should reconsider the site design if it mostly contains 1- and 2-bedroom apartment's buildings. Although the optimum solutions may not be implemented in practice, they may be useful as certain performance benchmarks during the planning process.

Figure 6.23 shows that the BAU scenario is the one with the lowest environmental impacts compared to the other scenarios. This can be explained by the fact that the total area of the office buildings is almost negligible compared to other two scenarios (table 6.7) and the number of the office employees is approximately 5,500 compared to 170,860 and 88,220 for the CW and HRHD respectively. Moreover, the majority of the residential dwellings are semi-detached or terraced houses which results in smaller population density compared to the CW and HRHD scenarios. The highest environmental impacts are attributed to the embodied emissions from the construction materials used for the construction of the post-event site followed by the emissions from visitors' transportation in the legacy phase.

In the CW scenario, the majority of the emissions result from the transportation of visitors in legacy phase. This is due to the high number of employees travelling daily to/from the site. The emissions from the energy and water used for the operation of buildings (mostly offices) in legacy phase are almost equal to the embodied emissions from the construction materials used for the post-event site redevelopment.

The HRHD scenario is the one which results in the highest total emissions. This can be explained by the fact that this scenario has the highest number of residents and a high number of employees. It can be seen that the majority of the emissions are attributed to the embodied emissions from the construction materials used during the post-event site redevelopment followed by the emissions from visitors' transportation.

The models described in this chapter can assist decision makers with estimating the GHG emissions resulting from each of the proposed scenarios. However, numerous social and economic factors and their trade-offs also have to be taken into consideration before stakeholders agree on a final solution.

6.9. Summary.

This chapter presented the description of the optimisation models which were developed in this work. The aim of the models is to evaluate and optimise the environmental burdens resulting from the whole life cycle of a mega-event project. The models take into account GHG emissions associated with the transportation of construction materials, visitors and officials, energy, water and construction materials used, and removal of wastewater. The models were applied to determine the total emissions resulting from the proposed 3 scenarios of the post-event site redevelopment of the London Olympic Park, which is the case study of this project.

The models provide valuable information in terms of the emissions resulting from each phase of the mega-event project for each scenario. Moreover, the results provide data on the energy and resource usage in specific areas and help to determine how changes in certain parameters can affect the overall results. Therefore, the models can help to identify the most optimum scenario in terms of its lowest environmental emissions. It was mentioned earlier that technological progress is not taken into account due to numerous uncertainties regarding the future technologies and their practical implementation.

It was identified that the highest share of the total GHG emissions is attributed to the legacy phase. The duration of the legacy phase in this project is assumed to be 25 years. It is obvious that the longer the legacy period the higher its environmental impacts resulting from the operation of buildings on site and transportation of visitors to/from the site. Therefore, the models described in this chapter can be a valuable tool for the decision makers involved in the environmental assessment of the proposed post-event site design scenarios. The models can help to evaluate the environmental burdens of the proposed scenarios, determine theoretical optimum performance benchmarks and define the optimum scenario in terms of their environmental impacts.

Chapter 7. Evaluation of the environmental impacts of the Integrated Waste Management Systems using Life Cycle Assessment.

This chapter provides the second part of the environmental assessment presented in Chapter 4. The environmental impacts of the integrated waste management systems are investigated for each of the proposed scenarios using the LCA technique. The chapter begins with a summary of recent developments in the application of LCA and explains why LCA is used in this work for the environmental assessment of waste management systems. Then the LCA methodology developed in this work is presented followed by the description of each of the 10 IWMSs investigated. The next part provides the LCA results in six impact categories considered in this study for all scenarios. The final section provides the results of the sensitivity and 'hot-spot' analyses followed by the discussion of results.

7.1. Introduction.

Management of the municipal solid waste (MSW) is one of the most significant problems in the European Union (EU) and in the UK due to increasing per capita waste generation, changes in waste composition, uncertainties in markets for recycled materials, need for investment in waste processing infrastructure, institutional and political impediments and a large set of stakeholders involved (Shmelev and Powell, 2006). In the last decade, the UK Government significantly improved its waste policy and developed a number of consecutive waste strategies such as the Waste Strategy for England (DEFRA, 2013c), Landfill Directive (DEFRA, 2010), and Waste Prevention Programme for England (DEFRA, 2013d). The main aim of these strategies is to reduce MSW generation, increase recycling targets for household and municipal waste, and divert waste from landfills.

Sustainable energy supply is another current major problem in the UK. The UK has to increase its domestic renewable energy significantly in order to mitigate climate change and reduce its dependence on energy supply from other countries. The UK Government has a target to source 15% of its overall energy consumption from renewables by 2020 (DECC, 2011). The target is very challenging. In 2012, 141

GWh of electricity generated in the UK came from renewable sources, which accounted for only 4.1% (DECC, 2013a).

In the last few decades waste management has evolved from the uncontrolled landfill or incineration of the total municipal solid waste (MSW) stream into a complex process where separate MSW fractions are treated at different waste processing facilities. Nowadays waste is no longer considered as an unwanted material, it is seen as a valuable resource. Energy, materials and nutrients recovered during waste treatment processes can substitute virgin materials and energy from the grid. It is argued that Energy from Waste (EfW) technologies can provide great opportunities for renewable energy generation and reduce environmental impacts associated with waste utilisation (Jamasb and Nepal, 2010). UK Government is determined to increase energy from waste generation due to the following reasons:

- Energy from waste is a valuable domestic source of energy that contributes to energy security;
- Waste is a low-carbon energy source that can contribute to the UK's renewable energy targets;
- Unlike wind and solar technologies, energy from waste has an advantage of being a non-intermittent energy source (DEFRA, 2013d).

Sustainable planning of Energy-from-Waste systems is a difficult task due to the availability of different waste treatment technologies and diverse markets for recovered energy and materials (Eriksson and Bisaillon, 2011). Waste treatment planning for mega-event projects such as the Olympic Games or FIFA World Cup is even more complex because of the long-term nature of such projects, involvement of various stakeholders and multiple project stages of different duration. Although the main focus of mega-event projects is the actual event, legacy is definitely the longest and the most important phase because this is where the long-term impacts will occur. Thus, waste management planning for mega-event projects should be embedded in the long-term city development plan with particular emphasis on the redevelopment and integration of a post-event site.

Environmental assessment of different waste management options is not a straightforward task because of a number of reasons. First of all, there are different waste treatment facilities and technologies and their environmental impacts vary significantly. Second, the environmental impacts resulting from treatment of the same amount of MSW using the same technology may differ considerably because of the differences in waste composition, particularly its organic content. Third, the recycling rates and the types of materials recycled differ between recycling facilities. Finally, the availability of various treatment facilities in a certain location, the costs and different waste treatment policies and strategies make each integrated waste system unique. Therefore, the emissions coefficient factor associated with the treatment of 1 tonne of MSW is also unique and has to be determined for each individual system. We identified Life cycle assessment (LCA) as the most suitable tool to use in this work as a part of the overall methodology for sustainability assessment presented in Chapter 4 (section 4.2).

This chapter illustrates how LCA can be applied in the planning process of waste treatment options for mega-event projects. 10 integrated waste management systems (IWMSs) have been evaluated for 3 proposed post-event site design scenarios in order to identify which ones will result in the lowest environmental burdens. The IWMSs investigated reflect the current UK waste management strategy in the UK which supports advanced treatment solutions, i.e. gasification and anaerobic digestion (AD) against traditional technologies such as incineration and landfill.

The chapter aims to address the following questions:

1. Which legacy scenario should be considered the ‘best option’ in terms of the lowest environmental impacts associated with waste treatment of MSW given a set of 10 IWMSs?
2. What type of waste management facilities can provide the optimum long-term solution and, therefore, should be implemented and why?

The next section provides a short summary of the application of LCA to the environmental assessment of waste management systems. Section 7.3 provides an overview of the LCA methodology developed for the current study. Section 7.4

7.2. Application of LCA to Waste Management Systems.

7.2.1. Recent developments in the application of LCA to the environmental assessment of MSW systems.

Life Cycle Assessment (LCA) is one of the most powerful environmental assessment tools that have been widely used for almost 40 years to evaluate the environmental impacts of a product or service during its entire life cycle. The applications of life cycle approach and LCA are now required by various EU legislations, such as the Directive on Integrated Prevention and Control (IPCC) and the Integrated Product Policy (IPP) (Azapagic et al., 2006). The main steps of the LCA methodology were described in chapter 2. Full details on LCA methodology are provided in the ISO Environmental Management standards (ISO, 2006a,b).

LCA has been applied to the environmental assessment of waste management systems since the early 1990s (Björklund et al., 2010, Manfredi et al., 2011). It is argued, however, that only a few recent LCA studies analysed MSW management from a system perspective covering the total waste stream and treatment of all fractions (Giugliano et al., 2011). Most LCA studies only examine the environmental impacts of a particular waste treatment technology (i.e. incineration, landfill or composting) (Astrup T., 2009; Boldrin et al., 2009; Manfredi et al., 2009; Møller et al., 2009), or of a single waste fraction (i.e. paper, food waste, plastics) (Merrild et al., 2008; Wang, 2012; Yoshida, 2012). These studies provide valuable data, however they cannot be used as a decision-making tool for municipal or regional waste strategies as they are unable to provide an overall view of an entire management system. It is argued that the system approach is essential and integrated waste management system should be analysed as a whole since the sub-systems are interrelated and advances in one area often lead to changes in practice in another area (Blengini et al., 2012a). In order to capture and evaluate all complexities and interdependencies, many recent LCA studies adopted an integrated system approach that evaluates the environmental impacts of a combination of different waste treatment technologies for separate MSW fractions generated in a particular area (Eriksson et al., 2005, Kirkeby et al., 2007, Buttol et al., 2007, De Feo and Malvano, 2009, Calabrò, 2009, Bovea et al., 2010).

Waste management systems are closely linked with energy systems as electricity and fuel are essential for the operation of waste treatment facilities and transportation. Moreover, waste is a valuable resource of renewable energy. Thus, most currently developed LCA models are considered multifunctional as they do not only evaluate environmental impacts of waste treatment processes, but also include emissions associated with energy consumed and avoided emissions from energy generated and materials recovered (Eriksson and Bisaillon, 2011; Assefa et al., 2005; Özeler et al., 2006; Chaya and Gheewala, 2007).

7.2.2. System boundaries, allocation and system expansion.

A choice of system boundaries has a great effect on the results and their interpretation in waste management LCAs (Mendes et al., 2004). The goal and scope definition of an LCA study has to provide a full description of a system and all activities considered in the study. Life Cycle Inventory has to include all energy and resource flows, and emissions associated with all activities in the system.

Integrated waste management systems are multi-functional systems that include waste treatment processes, energy and materials supplied for these processes, and energy and materials that are being recovered. When two or more products are produced in the same system, the allocation of the environmental burdens between these products must be clearly defined in order to include all significant emissions and avoid double-counting. In the context of LCA, the two approaches are normally used to distribute the environmental burdens: allocation and system expansion. Allocation is normally applied in traditional attributional LCAs. System expansion is normally used in consequential LCAs to expand the system and include substitution of other products (Fruergaard et al., 2009). Average data is normally used in attributional LCA to determine the overall environmental impact of the system. Consequential LCAs use marginal data to evaluate changes in the system. The drawback of a system expansion is that the model gets bigger, more complex and less transparent (Finnveden, 1999). The advantages of using system expansion are the ability of a system to reproduce the real situation and to avoid difficult allocations as recommended in the ISO standards (ISO, 2006a,b). A general outline of an LCA methodology with a system expansion is provided in figure 7.1.

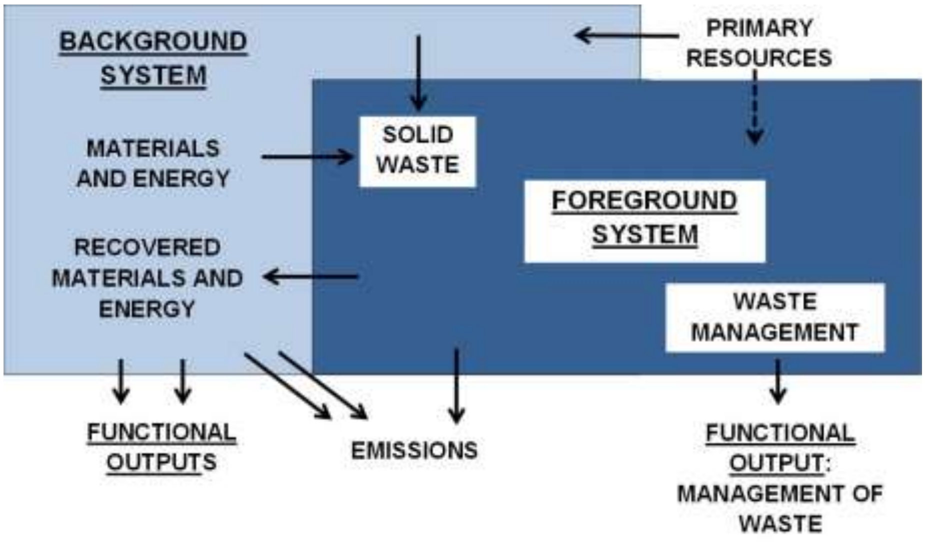


Figure 7. 1. General methodology of the LCA with a system expansion (Clift et al., 2000).

LCA with a system expansion includes foreground and background systems. The foreground system is a set of processes whose choice or method of operation is affected directly by decisions based on the study. The background system includes all other processes interacting with the foreground system, normally through materials and energy transfer (Clift et al., 2000).

7.2.3. Direct, indirect and avoided emissions.

Greenhouse gas emissions (GHG) associated with a particular waste treatment process are normally categorised into direct and indirect burdens. Direct burdens occur in the foreground system; they originate from the transportation of MSW and waste treatment processes themselves. Indirect burdens occur in the background system through transfer of materials and energy to/from the foreground system. Indirect burdens can be divided into upstream and downstream burdens (Clift et al., 2000; Bernstad and la Cour Jansen, 2012). Upstream burdens are those arising from the extraction and manufacturing processes, transportation and use of a given product prior to its final disposal. Normally waste LCA systems are modelled assuming a "zero burden", specifying that no embedded impacts from the production of a product before it becomes a waste are included (Gentil et al, 2010; Buttol et al., 2007). Upstream burdens also occur from the construction of infrastructure and manufacturing of collection vehicles. These burdens, however, are only accounted for in a very small number of LCA studies (Manfredi et al., 2009; De Feo and Malvano, 2009). In most LCAs on waste management these burdens are excluded (Buttol et al., 2007; Mendes et al., 2004; Møller et al., 2009; Slagstad and Brattebø., 2012; Consonni and Vigano, 2011). Upstream burdens associated with the provision of energy – electricity, diesel or oil are included in most LCAs (Andersen et al., 2012; Manfredi et al., 2009; Møller et al., 2009; Wittmaier et al., 2009). Downstream burdens, usually referred to as avoided burdens, associated with those economic activities which are displaced by materials, nutrients and energy recovered through waste treatment process (Clift et al., 2000). Most integrated waste management LCA studies include calculations of avoided burdens by displacing emissions associated with grid energy and virgin materials production by amounts of energy and materials recovered in a given system (Manfredi et al., 2009; Møller et al., 2009). Therefore, the total emissions are calculated as:

Total emissions = Direct emissions + Indirect Emissions – Avoided emissions

There is an on-going debate within an LCA community as whether biogenic carbon dioxide emissions should be accounted for or excluded from the inventory analysis. Biogenic carbon dioxide emissions are defined as emissions resulting from the combustion or decomposition of biologically-based materials other than fossil fuels (EPA, 2014). This refers mainly to CO_2 emissions because biogenic N_2O and CH_4 emissions are not part of the carbon cycle that occurs with regrowth of biomass and, thus, biogenic N_2O and CH_4 are dealt with the same way as fossil GHG emissions. Some LCA studies consider biogenic CO_2 emissions as neutral in relation to GWP (Boldrin, 2009). Other studies account for biogenic emissions, therefore GWP factor is considered to be 1 (Blengini, 2008a,b; Lee at al., 2007). Christensen et al. (2009) argue that biogenic CO_2 emissions can be seen both as neutral and contributing to GWP, as long as constant accounting method has been applied throughout a specific system and to all systems compared.

7.2.4. Functional Unit.

A definition of a functional unit (FU), which is the focus of the study, is equally important in LCA as establishing a system boundary. In a typical product LCA, a FU is generally defined in terms of the system's output, for example, per number of units produced. In a waste management LCA study, a FU must be defined in terms of systems' input, i.e. waste (Cherubini et al., 2009). Some LCAs calculate environmental burdens per kg or tonne of waste generated. These studies allow comparison of different waste treatment processes, but do not account for the changes in waste quantity. Thus, they are inadequate for the assessment of waste management strategies (Ekvall et al., 2007). When LCA is used as a decision making tool for a specific geographical region, a FU should be chosen as the total waste produced in this region in a given time (i.e. one year) (Cherubini et al., 2009).

7.3. LCA methodology developed in this project.

The goal of this LCA study is to determine environmental impacts of the integrated waste management systems proposed for the treatment of MSW generated at the London Olympic Park during the Games period and in one year of post-event period (for three scenarios). The overall LCA methodology developed for this project is provided in figure 7.2.

The foreground system (highlighted in grey in figure 7.2) includes emissions associated with different waste treatment facilities considered in the study: anaerobic digestion (AD), composting, materials recovery facility (MRF), mechanical biological treatment (MBT), Energy-from-Waste (EfW) via incineration, advanced thermal treatment (ATT) and landfill. Emissions resulting from the transportation of MSW to/from the transfer station to the waste treatment plants and emissions from the transportation of compost and digestate to the arable land are also included in the foreground system. The background system includes supply of electricity, diesel and other materials to the foreground system (indirect emissions), and production of chemical fertilizers and virgin materials (avoided emissions).

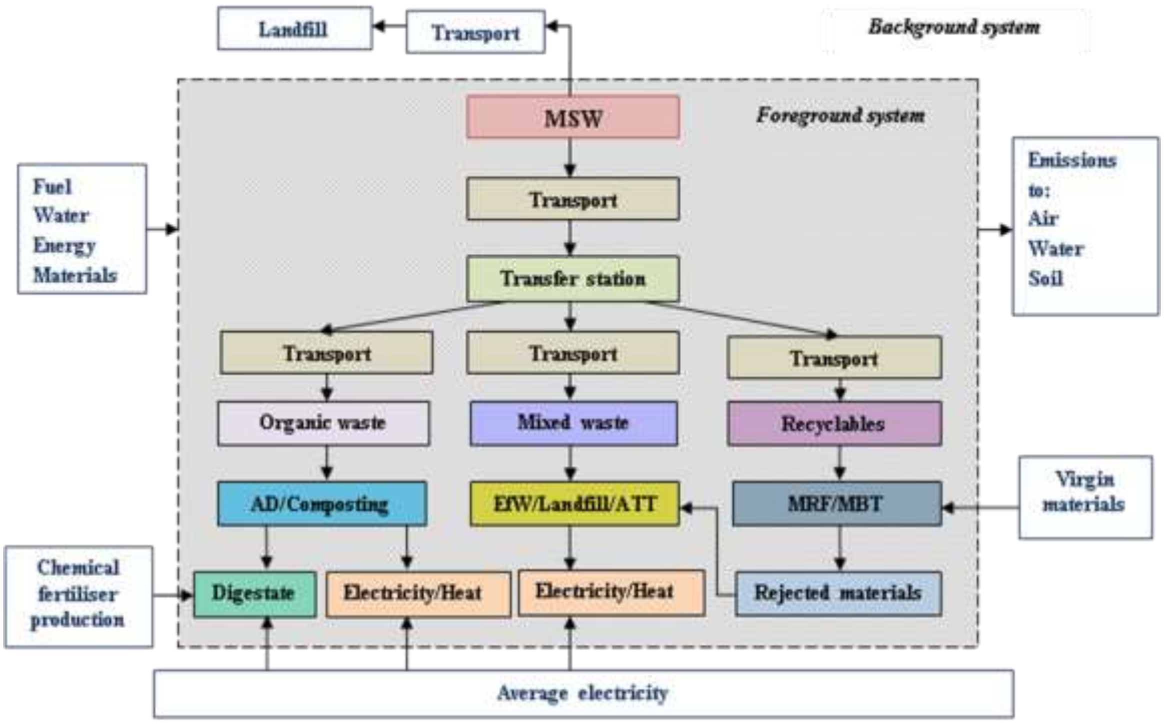


Figure 7. 2. Overall LCA framework developed for environmental evaluation of the integrated waste management systems analysed in this project.

The system described in this paper was modelled assuming a 'zero burden' from generation of MSW. Direct emissions include emissions associated with waste treatment processes; indirect emissions include emissions from energy and materials supplied to the system; avoided emissions include those associated with displacement of production processes of materials, nutrients and energy recovered through waste treatment processes. In this work, biogenic carbon is accounted for in all processes. Detailed description of the integrated waste management systems analysed in this study and waste treatment processes are provided in section 7.6.

7.4. GaBi V.6 Product Sustainability Software.

At present, there are about thirty software packages available to carry out LCA analysis. In this study GaBi Product Sustainability Software has been used (GaBi, 2013). GaBi software calculates life cycle impacts of the products or services based on the inventory of emissions and materials associated with a product's life cycle. Each step of a product's life cycle is modelled as a process flow-sheet that analyses materials and energy flows in the system. GaBi software was chosen because it includes extensive database developed by PE International which is updated on a regular basis. GaBi software also integrates other databases (e.g. Ecoinvent, national and regional databases) for specific processes and geographical locations.

7.5. Inventory data and assumptions.

7.5.1. Waste composition and recycling rates.

7.5.1.1. Quantity and composition of MSW generated during the Games period.

The amount of waste generated at the London Olympic Park during the actual event was estimated based on the information provided by the ODA (London2012, 2012). It was estimated that the total amount of waste generated during the Games was 10173 tonnes, of which 60% was generated in the Olympic Park. Therefore, it is assumed that 6103 tonnes of waste was generated during the Games in the Olympic Park. Quantities and composition of MSW in the Olympic Village is assumed to be the same as in the residential dwellings (see section 7.5.1.2). Quantities and composition of MSW in the Broadcast and Media centres were assumed to be the same as in the typical office buildings (see Appendix 1). Quantities and composition of MSW generated at the sports venues are based on the estimated composition of waste produced during the sporting events (RW, 2013) (table 7.1). The overall recycling rate in the sports venues is assumed to be 70% (London2012, 2009).

Table 7. 1. Composition of waste generated in the sports venues (RW, 2013).

	Paper and cardboard	Organic waste	Plastics	Glass	Metals	Others
MSW fractions (% of the total MSW)	33	5	9	28	0	25
Amount of MSW fractions (tonnes)	1655	251	451	1405	0	1254

7.5.1.2. Annual quantity and composition of MSW generated in the post-event period.

The amount of MSW generated in residential buildings was calculated based on the estimations that each resident produces 457 kg of MSW per year (DEFRA, 2011). The average data on waste composition in England is provided in Figure 7.3.

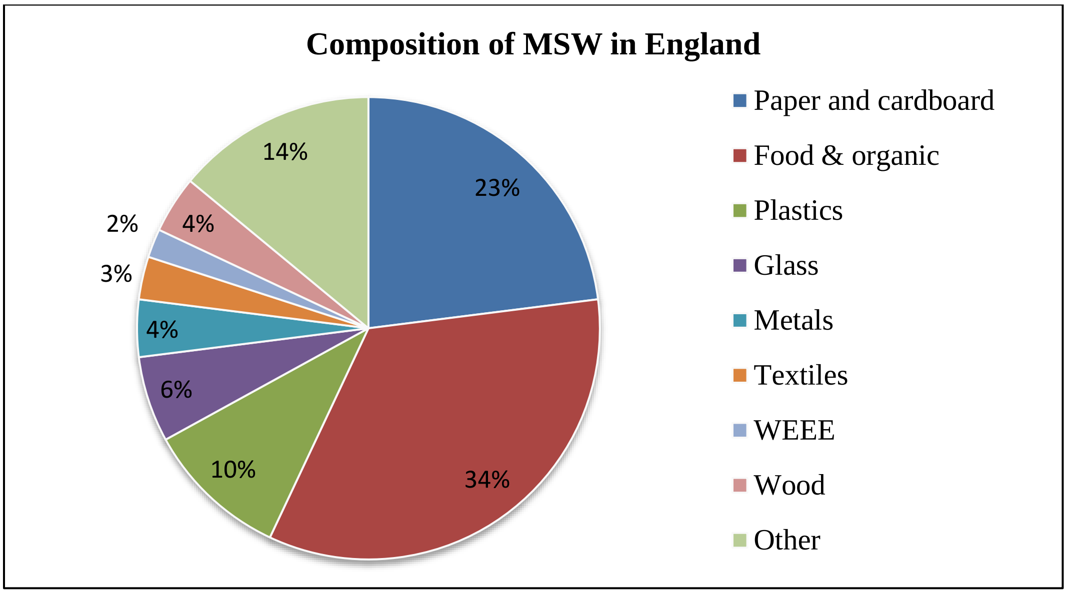


Figure 7. 3. Composition of MSW in England (adapted from DEFRA, 2013a).

Recycling rates for MSW in England range from 23% to 42% depending on the area, materials recycled and collection schemes (EA, 2010). Household recycling rate in London is estimated to be 40% (EEA, 2013). Annual waste quantities generated in the non-residential buildings were calculated based on the number of different types of buildings in each of the proposed post-event site design scenarios described in detail in appendix 2.

Table 7.2 provides the quantities of the MSW generated per year in all types of buildings for each of the proposed post-event site design scenario calculated in the model described in section 6.6.1. Data on waste quantities generated in different types of non-residential buildings is provided in Appendix 1.

Table 7. 2. Quantities of waste generated in one year of post-event period for three scenarios.

	BAU	**CW**	**HRHD**
Residential buildings	8309	2883	20086
Offices	1103	29074	19408
Sports Venues	159	159	159
Restaurants	4200	3240	6780
Schools and nurseries	818	284	1978
Hotels	339	947	2759
Retail units	600	1000	3000
Medical centres	319	110	769
Total	**15847**	**37697**	**54939**

Composition of waste in non-residential venues varies significantly depending on a venue type. A summary of waste composition for non-residential venues is provided in table 7.3.

Table 7. 3. Waste composition in non-residential venues (% of the total waste quantity).

	Paper and cardboard	Organic waste	Plastics	Glass	Metals	Others	Reference
Offices, medical centres	60	21	7	3	3	6	UoE, 2011
Restaurants	24	44	9	14	3	6	WRAP, 2011
Secondary schools	53	20	14	2	3	8	Biffa, 2012
Primary schools, nurseries	53	13	12	3	3	1	Biffa, 2012
Sports venues	33	5	9	28	0	25	RW, 2013
Hotels	25	37	15	10	5	8	WRAP, 2011
Retail	40	36	17	1	0	6	WRAP, 2011

Recycling rates in non-residential buildings also vary significantly and depend on the venue type, recycling strategies and targets in a specific area, and provision of the recycling containers on the premises. Table 7.4 provides the data on the recycling rates that was applied in this project.

Table 7. 4. Average recycling rates in various types of residential and non-residential buildings.

	Residential houses	Restaurants	Offices, medical centres	Schools, nurseries	Sports Venues	Hotels	Retail
Recycling rate	40%	46%	67%	45%	70%	63%	61%
Reference	EA, 2010	WRAP, 2011	UoE, 2011	Biffa, 2012	RW, 2013	WRAP, 2011	WRAP, 2011

7.5.2. Functional Unit.

It is reported that when LCA is used as a decision making tool for a specific geographical region, the functional unit (FU) should be chosen as the total waste produced in this region in a given time (i.e. one year) (Cherubini et al., 2009). In this project, the functional unit for the Games period is the amount of MSW generated at the Olympic Park throughout the duration of the event. The functional unit for the Legacy period is the amount of MSW generated in all buildings of the post-event site (for 3 design scenarios described in section 4). Functional units for each of the scenarios evaluated in this study are provided in table 7.5.

Table 7.5. Functional units for Games period and for each of the 3 post-event scenarios in Legacy period.

	Games	Legacy (1 year)		
		'Business As Usual'	'Commercial World'	'High rise-high density'
Functional Unit (tonnes of MSW)	6103	15847	37697	54939

7.5.3. Transport of waste and transportation distances.

As it was mentioned earlier, emissions resulting from the transportation of waste to the transfer station and to waste treatment facilities are included in all scenarios. Collection of waste from individual households and home pre-treatment of waste for recycling are not included. Distances between the transfer stations and various facilities were calculated based on the locations of the nearest plants, farmland and landfill site. They are provided in table 7.6.

Table 7. 6. Transportation distances considered in the current study.

	Transfer station	MRF, MBT, Composting	EfW, ATT	AD facility	Landfill	Farmland
Distance (km)	7	20	20	130	26	50
Assumed location	London Borough of Hackney	Edmonton, London Borough of Enfield	Edmonton, London Borough of Enfield	Westwood, Northamptonshire	Rainham, Essex	Essex

The collection vehicles were modelled as Euro 3 trucks with payload capacity of 9.3 tonnes and diesel consumption of 2.18 kg per tonne of cargo and volumetric capacity of 50 m^3 (GaBi, 2013). The same type of truck is assumed to be used for transportation of all waste fractions to all facilities.

7.5.4. Impact categories considered in the current study.

The environmental impacts of the proposed integrated waste management systems in the current study were evaluated using CML 2001 characterisation method (Guinée et al., 2002). The following impact categories were considered:

- Global Warming Potential (GWP) – accounts for the emissions of greenhouse gases over 100 years,
- Acidification Potential (AP) – accounts for the emissions of gases causing 'acid rain' formation, such as NO, N_2O, NO_x, NH_3, HCl and HF,
- Eutrophication Potential (EP) – accounts for nutrients causing an increase in the rate of supply of organic matter in an ecosystem, such as Volatile Organic Compounds (VOCs), mainly Non-Methanic VOCs (NMVOCs),
- Abiotic Depletion Potential fossil (ADP) – accounts for the amount of energy contained in raw materials. with the amount of energy contained in raw materials,
- Photochemical Ozone Creation Potential (POCP) - accounts for pollutants causing the formation of harmful low-level (VOCs, NO_x),
- Human Toxicity Potential (HTP) – presents evaluations of hazard based on the toxic potency of a substance and the potential dose in a unit.

7.5.5. Avoided burdens.

Avoided burdens in the background system are calculated according to the amount of energy recovered in the Energy-from-Waste facilities, quantity of materials recovered at the MRF and the quantity of nutrients recovered at the composting or AD facilities. The energy recovered from waste can displace the equivalent amount of the average UK grid heat and electricity and, subsequently it can displace emissions associated with them. Recycled materials can substitute virgin materials displacing emissions resulting from the production of virgin materials.

In this project it is assumed that both electricity and heat recovered from waste will be utilised, as well as recovered materials from MRF and nutrients from compost and digestate. Table 7.7 provides results of environmental impacts of a production of 1

MJ of the average UK electricity and heat in 6 impact categories considered in the study.

Table 7. 7. Environmental burdens resulting from the production of 1 MJ of electricity and heat (UK grid) (GaBi, 2013).

	Electricity grid mix UK	Heat from natural gas boiler UK
GWP (kg CO2 eq)	1.53E-01	1.90E-02
AP (kg SO2-eq)	5.30E-04	1.20E-05
EP (kg Phosphate-eq)	4.50E-05	7.80E-07
AD fossil (MJ)	2.60E+00	3.15E-01
POCP (kg Ethene-eq)	3.00E-05	2.92E-06
HTP (kg DCB-eq)	2.40E-02	1.90E-04

Materials recovered at a recycling facility are mixed paper, mixed plastics, glass and metals. Emission credits for the substitution of virgin materials by recycled ones are modelled using data on the emissions associated with the production of virgin materials from the Ecoinvent database (2014) and provided in table 7.8.

Table 7. 8. Environmental burdens resulting from the production of 1 kg of each virgin material (Ecoinvent, 2014).

	Aluminium	Ferrous metals	Glass	Paper	Plastics
GWP (kg CO2 eq)	1.02E+01	2.64E+00	8.10E-01	5.20E-01	1.95E+00
AP (kg SO2 eq)	5.41E-02	5.81E-03	7.60E-03	3.74E-03	6.56E-03
EP (kg Phosphate eq)	2.53E-03	3.79E-04	1.30E-03	1.73E-03	4.29E-04
ADP (MJ)	1.28E+02	2.92E+01	1.39E+01	2.02E+01	7.15E+01
POCP (kg Ethene eq)	3.19E-03	8.23E-04	3.54E-04	3.54E-04	1.24E-03
HTP (kg DCB eq)	7.90E+00	5.40E-02	4.54E-01	4.54E-01	8.52E-01

Digestate and compost can be applied on arable land instead of mineral fertiliser. The production of mineral fertiliser requires the use of energy and other materials which results in emissions. Due to the availability of data, only those emissions that account for GHGs are considered in this study. The ranges of GHGs emissions can vary due to the energy mix considered for electricity production and different production technologies. GHGs emissions per kg on nutrients produced are: 4.75-13.0 kg CO_2-eq for N fertilisers, 0.52-3.09 kg CO_2-eq for P fertilisers and 0.38-1.53 kg CO_2-eq for K fertilisers (Boldrin et al., 2009). In this study the UK values suggested by DEFRA

(Williams et al., 2006) are used for the substitution of emissions resulting from the production of mineral fertilisers. They are provided in table 7.9.

Table 7. 9. Emissions resulting from the production of mineral fertiliser (Williams et al., 2006).

Mineral fertiliser	kg CO_2-eq/kg fertiliser
Nitrogen (N)	6.8
Phosphorus (P)	1.2
Potassium (K)	0.5

7.6. Integrated waste management systems.

The combination of the following waste treatment facilities were considered in the integrated waste management systems developed in this project: Materials Reclamation Facility (MRF), Mechanical Biological Treatment (MBT), Anaerobic Digestion (AD) plant, Composting facility, Energy from Waste (EfW) incineration plant, Advanced Thermal Treatment (ATT) facility, and landfill site. Figure 7.4 provides a general scheme of the 10 integrated waste management systems (IWMSs) evaluated in this study. A detailed description of all scenarios is provided in sections 7.6.1-7.6.6.

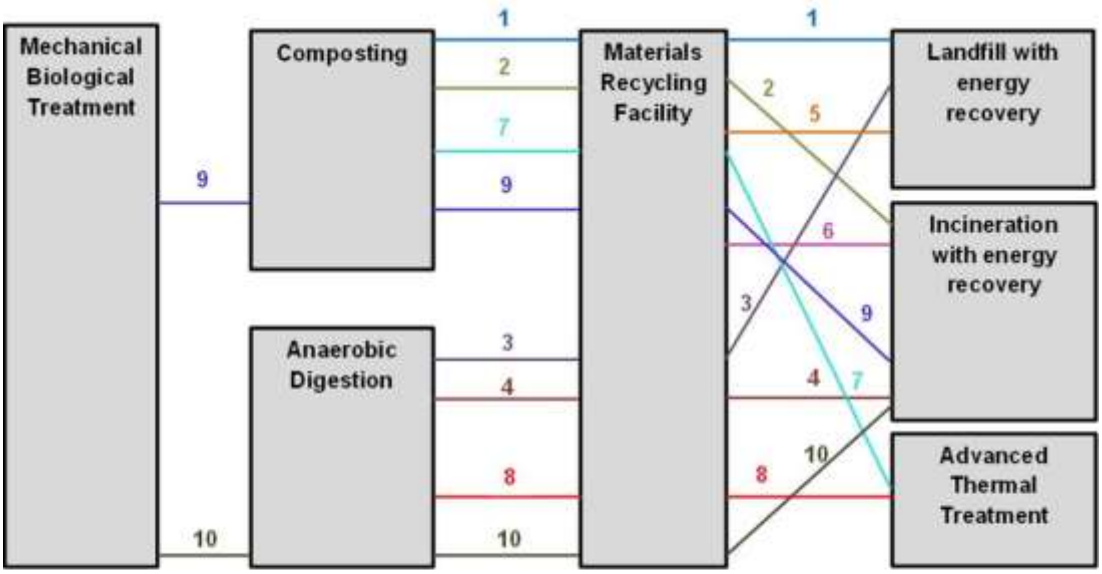


Figure 7. 4. Overall scheme of the 10 integrated waste management systems.

7.6.1. IWMS 1. Composting, MRF, Landfill.

In IWMS 1, the total MSW stream is divided into three groups: organic fraction of municipal solid waste (OFMSW), source-separated recyclable materials, and residual unsorted MSW. The three fractions are treated separately: OFMSW is sent to the composting plant, recyclable materials are sorted out at the Materials Recovery Facility (MRF), and the residual unsorted waste is sent to landfill. Rejected materials from the MRF and composting facility are also sent to landfill.

Composting facility:

Direct burdens from composting include emissions to air due to degradation of the organic matter, emissions to land, ground water and surface water. Indirect burdens include provision of diesel and electricity for transportation and pre-treatment of OFMSW and spreading of compost on arable land. In this study emissions were modelled using data from DEFRA (2004). The amount of CO_2, CH_4 and N_2O that are emitted to the atmosphere during the composting process and application of compost on farmlands were calculated using the methodology provided by Boldrin et al. (2009) on the basis of the composition of the organic waste used in this study, see table 7.10.

Table 7.10. Characteristics of OFMSW (Zhang et al., 2012).

	Value	Unit
Total Solids	24	Fraction of a wet feedstock (by mass)
Volatile Solids	91	% of Total Solids (TS)
C content	47.6	% of TS
K content	3.43	% of TS
N content	3.44	% of TS
P content	1.29	% of TS

It is assumed that compost complies with PAS 100 (BSI, 2005) standards and can be applied on arable land instead of a mineral fertilizer. Avoided burdens account for the substitution of mineral fertilizer with nutrients (nitrogen N, phosphorus P and potassium K) recovered during composting processes and for the amount of carbon that stays bound in the soil after 100 years. Potential amounts of inorganic fertilizers replaceable by use of compost are 3 kg/t waste for N, 1.4 kg/t waste for P and 3.8

kg/t waste for K based on the compost output of 400 kg per 1000 kg of treated food waste (Boldrin et al, 2009). The amounts of carbon still bound in the soil after 100 years is estimated to be 2-14% depending on the type of soil and crop replacement (Smith et al., 2001, Bruun et al, 2006). In this project the amount of carbon bound in the soil is assumed to be 7%.

Materials Recovery Facility:

In this project, a typical dry MRF process is considered (WRAP, 2007). After collection, MSW is transported to a transfer station where it is stored before being transported to the MRF. At the transfer station, 0.4 litre of diesel and 1 kWh of electricity are used for operating the machinery (per tonne of waste). At the MRF, 25 kWh of electricity and 3.4 litre of diesel are used for machineries' operation (Merrild et al., 2012). Four waste streams are assumed to constitute the recycling streams at MRF: glass, mixed plastics, mixed paper, and metals. In this study, metals' content has been assumed to consist of 30% non-ferrous and 70% ferrous metals (Cimpan and Wenzel, 2013). Not all materials sent to the MRF will be recycled. The quantity of rejected material varies depending on the type of MRF, its management, and the level of contamination in the incoming feedstock (WRAP, 2006). In this study the reject rate for all fractions is assumed to be 10%, which is the average number for most MRFs in the UK (Palm, 2009). The quantities of waste streams sent for recycling were estimated based on the total amount and composition of waste from residential and non-residential venues (table 7.11).

Table 7. 11. Quantities of waste streams sent to the MRF for recycling.

	Paper and cardboard	Plastics	Glass	Metals	Total
Games	1,410	384	427	24	2,245
'Business as Usual'	2,138	672	565	246	3,620
'Commercial World'	12,504	1663	909	688	15,764
'High rise, high density'	11,460	2,249	1,439	883	16,032

The amount of electricity, natural gas and diesel used for the reprocessing of different recycling streams is provided in table 7.12.

Table 7. 12. Amount of energy used for the reprocessing of different recycling streams.

	Energy required	Unit	Reference
Aluminium	24	MJ/kg primary energy	Cimpan and Wenzel, 2013
Copper	28	MJ/kg primary energy	Cimpan and Wenzel, 2013
Ferrous metals	9	MJ/kg primary energy	Cimpan and Wenzel, 2013
Plastics	4	MJ/kg electricity	Cimpan and Wenzel, 2013
Plastics	1.1	MJ/kg natural gas	Cimpan and Wenzel, 2013
Paper	1.13	MJ/kg electricity	Wang et al, 2012
Paper	6.764	MJ/ kg natural gas	Wang et al, 2012
Paper	0.037	kg/kg diesel	Wang et al, 2012
Glass	0.5	L/tonne diesel	Blengini et al, 2012b
Glass	104	MJ/tonne natural gas	Blengini et al, 2012b
Glass	25	kWh/tonne electricity	Blengini et al, 2012b

The model of the MRF includes emission credits for the substitution of virgin materials with reprocessed materials. Substitution ratio between virgin and recycled materials is often highly dependent on the type of recycling technology and the material recycled. It is argued that newer processes will tend to have a substitution ratio closer to 1:1 (Gentil et al., 2010). Thus, substitution ratio in this study is also considered to be 1:1.

Landfill site:

In this work a conventional UK landfill is modelled to include leachate and gas handling. The model does not include active measures for waste degradation that are used in engineered landfills, such as leachate recirculation or air injection (Manfredi and Christensen, 2009). Distribution of landfill gas is: 22% flare, 28% utilisation for electricity production and 49% are emissions to the atmosphere. The landfill model takes into account leachate treatment, sludge treatment, landfill gas flare, and landfill gas Combined Heat and Power (CHP) unit. The composition of waste (particularly a quantity of organic waste in a total waste stream) and site location play a significant role in the amount of landfill gas generated and the emissions produced at a landfill site. Thus, site specific data is used in this model (DEFRA, 2004). The model also takes into account fuels required for on-site machinery operation and electricity and thermal energy to be used on-site.

7.6.2. IWMS 2. Composting, Recycling, Incineration with energy recovery.

In IWMS 2, the total MSW is divided in three groups like in IWMS 1. Recyclable materials are sent to the MRF, OFMSW is sent to a composting facility and the residual waste is sent to an Energy-from-Waste incineration plant. Composting and Recycling plants and the amount of waste sent to these facilities are assumed to be the same as in IMSW1.

Energy-from-Waste plant:

In this project, a model for the incineration facility is based on the data for a typical UK EfW plant that meets the EU legal requirements. The plant consists of an incineration line fitted with a grate and a steam generator. Part of the steam produced internally is process steam, part is used to generate electricity, and the excess is exported to the district heating network. The average efficiency of the steam production is 82% (GaBi, 2013). The net electrical efficiency of the incinerator considered in this study is 16% and the thermal efficiency is 43% (Murphy and McKeogh, 2004). The losses of electricity associated with export are assumed to be 7%. The model of the EfW plant considers the flue gas treatment, the NO_x removal system, the treatment of air pollution control (APC) residues and bottom ash, and the credits for metals' recovery. Credits for electricity and heat are modelled using data for the average UK energy mix (GaBi, 2013).

7.6.3. IWMSs 3 and 4. Anaerobic Digestion, Recycling, Landfill with energy recovery/Incineration with energy recovery.

IWMSs 3 and 4 include the same processes as scenarios 1 and 2 apart from the facility for the treatment of the organic fraction of waste. In IWMSs 3 and 4, OFMSW is sent to the anaerobic digestion (AD) plant. There are different AD plants operating at different process conditions.

Anaerobic Digestion Plant:

The AD process considered in this work is a continuous single stage, mixed tank reactor operating at a mesophilic temperature of $35^{o}C$ (Evangelisti et al., 2013). The amount of heat required for the AD process, including the pre-treatment of waste, is assumed to be 13% of the total amount of biogas produced (MJ), the amount of electricity required for the AD process is estimated to be 11% of the total biogas produced, the additional electricity for dilution of waste is estimated to be 33 MJ per tonne of waste (Berglund and Börjesson, 2006). The amount and composition of the biogas produced varies significantly depending on the operating conditions and waste characteristics. In this project, the biogas production is calculated to be 118 Nm^3/tonne of waste. The average volume of methane is 63% and net calorific value of biogas is 23 MJ/Nm^3 (Fruergaard and Astrup, 2011). Biogas produced in the AD process is combusted in a CHP unit to generate energy. The electrical efficiency of the CHP unit is assumed to be 33% and the thermal efficiency is 52% (Zglobisz et al., 2010). Emissions from the combustion of biogas including start and stop of the engine are based on the data provided by Nielsen et al. (2008). The digestate produced during the AD process is assumed to be used as a substitution for chemical fertilizers with substitution rates of 100% for P and K and 40% for organic N (Møller et al., 2009).

7.6.4. IWMSs 5 and 6. Recycling, Landfill with energy recovery/Incineration with energy recovery.

Waste treatment processes for IWMSs 5 and 6 exclude separate treatment of OFMSW. Using data provided in section 7.5, it was calculated that the following amounts of OFMSW are used in the biological treatment facilities (AD or composting): Games – 251 t; legacy scenarios: BAU – 2360 t, CW – 5237 t, HRHD – 7339 t. In IWMSs 5 and 6 it is assumed that all OFMSW goes to landfill or the incineration plant. The quantities of OFMSW used in IWMSs 5 and 6 are: Games – 305 t; legacy scenarios: BAU – 5032 t, CW – 8563 t, HRHD – 14182 t.

7.6.5. IWMSs 7 and 8. Composting/AD plant, Recycling, ATT.

In IWMSs 7 and 8, Advanced Thermal Treatment (ATT) (gasification) processes replace conventional processes of landfill and incineration for treating the residual MSW stream. The total waste is separated into 3 main streams as in scenarios 1 and 2. OFMSW is treated in the composting plant in IWMS 7, and in the AD plant in scenario 8. Composting, AD and recycling facilities in IWMSs 7 and 8 are identical to those modelled in the previous scenarios.

Advanced Thermal Treatment (ATT) process:

ATT processes, such as gasification and pyrolysis, have several potential benefits over traditional combustion of solid wastes. ATT of municipal waste can reduce volume of solid waste, prevent dioxin formation, and reduce thermal NO_x formation (Zhang et al., 2012). Another advantage of ATT is better electrical generation efficiency compared to incineration. However, thermal efficiency of ATT processes is typically lower than that produced by incineration (Murphy and McKeogh, 2004). This is mainly due to the energy required to sustain gasification or pyrolysis processes (DEFRA, 2013a). Net electrical and thermal efficiency of the gasification process modelled in the current study are assumed to be 27 % and 24 % respectively (Murpy and McKeogh, 2004).

Emissions associated with this process are NO_x, SO_2, CO, CO_2, HCl, HF, dust, Cadmium, Mercury, Lead and Dioxins. The emissions were modelled according to Khoo (2009), Klein (2002), and DEFRA (2004). The amount of energy required for start-up of the plant and for converting MSW into refuse derived fuel (RDF) are 397 kWh and 18.4 kWh/tonne respectively (Khoo, 2009). The average syngas yield is assumed to be 1.3 Nm^3 /kg MSW; low calorific value (LHV) of syngas is assumed to be 8.4 MJ/Nm^3 (Zhang et al, 2012).

7.6.6. IWMSs 9 and 10. MBT, Composting/AD, Recycling, Incineration.

Mechanic Biological Treatment (MBT) plants were modelled in IWMSs 9 and 10. IWMS 9 includes a composting facility and IWMS 10 includes an AD plant for treating OFMSW.

Mechanical Biological Treatment (MBT) is a general concept of an integrated residual waste treatment system that includes both mechanical and biological treatment, such as Materials Recovery Facilities (MRFs), composting and Anaerobic Digestion plants. An MBT plant can consist of a combination of various processes and can be built for a range of purposes. The main aims of the MBT plants are the pre-treatment of waste before it is sent to landfill, diversion of non-biodegradable waste from landfill through mechanical sorting of MSW or recovery as RDF, diversion of biodegradable waste from landfill through conversion to biogas or compost-like output (DEFRA, 2013b).

MBT process:

The MBT process modelled in this study consists of two types of recycling facilities: a biological facility for the treatment of organic waste (composting facility in IWMS 9, AD plant in IWMS 10) and an MRF facility for the dry recyclables. It was estimated that MBT systems can recover 15-20% more materials from residual waste through various waste separation techniques (CIWEM, 2013). In this project it is assumed that 15% of each waste fraction will be recovered in the MBT plant. In IWMS 9, the organic fraction recovered in the MBT process will be treated in the AD plant and the digestate will be used on arable land in compliance with PAS 110 (BSI, 2010). In IWMS 10, the organic fraction will be sent for composting. In the UK, MBT composts do not qualify for certification under PAS 100 (EA, 2009) and, therefore, cannot be used as a fertilizer on arable land. Therefore, no avoided burdens are considered for nutrients recovery for MBT composting. Anaerobic digestion and composting plants in IWMSs 9 and 10 are assumed to have the same operational conditions as in the previous scenarios. The residual waste is sent to the EfW incineration plant. The amount of RDF sent to the EfW plant is estimated to be 376 kg per tonne of incoming waste (DEFRA, 2004).

Emissions from MBT systems include air and waste water emissions similar to those of windrow composting. Air emissions mainly consist of CH_4, CO_2, CO, NH_3, NO_x, SO_x; waste water emissions are ammonia, nitrates, sulphates and COD. Emissions in this study are modelled based on the data provided by DEFRA (2004).

7.7. Results and discussions.

A complete life cycle assessment of 10 integrated waste management systems was carried out for the Games period and for each of the 3 potential post-event design scenarios. Section 7.7.1 presents the results for the total environmental impacts for the Games period. Sections 7.7.2-7.7.4 presents the results for the total environmental impacts for three post-event site design scenarios. Section 7.7.5 provides the LCA results for 1 tonne of MSW treated. Section 7.7.6 describes the outcomes of the hot-spot analysis, which is carried out to identify which parts of the waste treatment processes are the highest contributors of the environmental burdens and savings. Section 7.7.7 provides the results of the sensitivity analysis which is carried out to identify how changes in certain parameters affect the overall results. The overall outcomes are summarised in section 7.8.

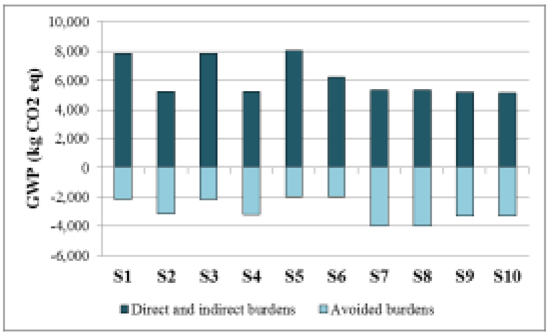
7.7.1. Life Cycle Assessment results for the Games period.

Table 7.13 shows the results of the total environmental impacts (direct and indirect burdens – avoided burdens) of the proposed integrated waste-to-energy systems (S1-10) for the Games period in 6 impact categories. In waste management LCA, positive results describe a load to the environment or resource use, while negative values show environmental savings. Savings occur when avoided burdens are larger than impacts associated with waste treatment processes. Thus, a negative value indicates an avoided burden (environmental benefit) and the positive one specifies an environmental burden.

Table 7. 13. Total environmental burdens (direct + indirect burdens – avoided burdens) for 10 IWMSs (S1-S10) for the Games period in 6 impact categories. High environmental burdens are highlighted in red, low environmental impacts and high avoided burdens are highlighted in green.

	GWP (t CO2 eq)	AP (kg SO2eq)	EP (kg Phosphate eq)	ADP (GJ)	POCP (kg Ethene eq)	HTP (t DCBeq)
S1	**5,706**	-5,854	**-353**	-20,330	**-107**	**-1,042**
S2	2,054	-7,617	-2,765	-38,918	-1,037	-1,100
S3	**5,676**	-5,953	**-405**	-20,683	**-100**	**-1,101**
S4	2,024	-7,717	**-2,818**	-39,271	-1,030	**-1,158**
S5	**6,059**	**-5,290**	**-140**	**-17,366**	**-55**	-1,072
S6	4,247	**-5,314**	-2,602	**-19,057**	-821	-1,067
S7	**1,340**	**-9,285**	**-2,831**	**-43,415**	-1,011	-1,080
S8	**1,321**	**-9,343**	**-2,880**	**-43,573**	-1,001	-1,137
S9	1,867	**-5,324**	-2,071	-42,511	**-2,541**	**-1,176**
S10	1,829	-5,449	-2,137	-42,953	**-2,532**	**-1,248**

Avoided burdens in this study stem from: the substitution of renewable electricity and heat with emissions associated to the equivalent electricity and heat produced from the fossil fuels; substitution of recovered metals, glass, paper and plastics with emissions associated with the production of equivalent virgin materials; and substitution of nutrients recovered through biological treatment with emissions associated with the production of chemical fertilisers. Figures 7.5 – 7.10 show direct and indirect burdens and avoided burdens for the Games period for each of the 10 integrated waste management systems (S1-S10) in 6 impact categories.



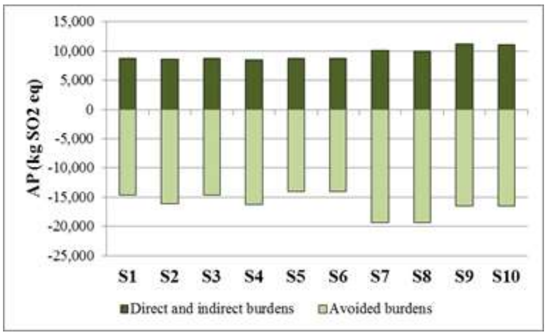
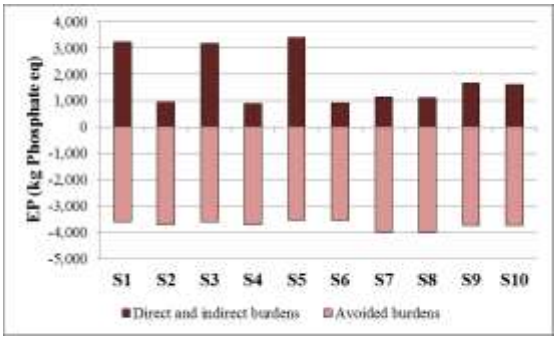


Figure 7. 5. GWP – Games period.

Figure 7. 6. AP – Games period.



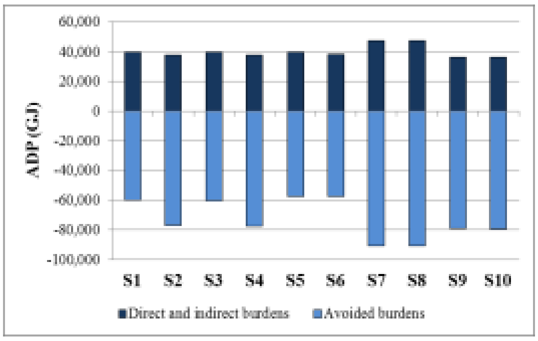


Figure 7. 7. EP – Games period.

Figure 7. 8. ADP – Games period.

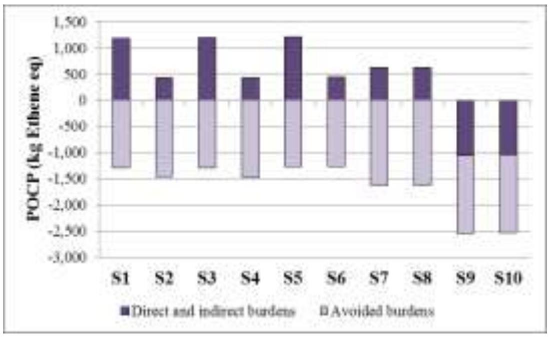


Figure 7. 9. POCP – Games period.

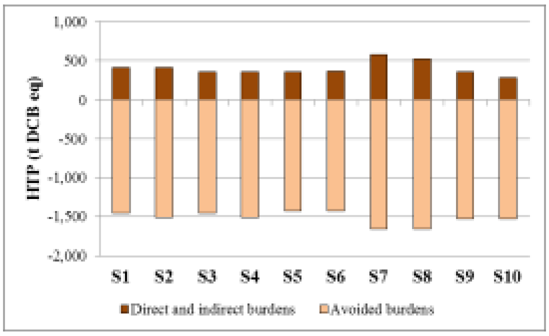


Figure 7. 10. HTP – Games period.

From table 7.13 it can be seen that IWMSs 1, 3 and 5 have the highest total environmental burdens for the GWP, EP, POCP and HTP. This is because landfill with partial gas utilisation is the primary waste treatment technology in these scenarios. During the waste degradation process at landfill sites high quantities of methane are generated (approximately 20 kg CH_4 per 1 tonne of MSW). In this study, it is estimated that 0.369 MJ of electricity can be generated from 1 kg of MSW at the landfill site under the operating conditions described in section 7.6.1. The avoided burdens from a landfill site are modelled considering the same amount of grid electricity being displaced with the electricity generated from landfill gas. The amount of energy generated from landfill gas is significantly less than the amount of energy generated from the EfW or ATT plants (1.03 MJ and 2.95 MJ respectively). At the same time, the emissions associated with a landfill process are higher than those resulting from other waste treatment facilities. Thus, IMSWs where landfill is the primary treatment option show the worst environmental performance in most categories. These results are in agreement with other LCA studies on waste management that showed that landfill technology is still the worst environmental option (Bovea et al., 2010; Cherubini et al., 2009).

The GWP for all IWMSs have positive values, which means that avoided burdens are lower than direct and indirect burdens. IWMSs 7 and 8 have the lowest GWP values (1340 and 1321 t CO_2-eq respectively). IWMSs 7 and 8 also show the highest environmental savings in terms of AP, EP and ADP. This can be explained by the fact that Advanced Thermal Treatment (gasification) is the primary waste treatment technology in these two systems. The amount of CO_2 released into the atmosphere is lower than during incineration, hence explaining a lower GWP. It was estimated that 2.95 MJ of electricity and 2.62 MJ of heat can be produced from 1 kg of MSW treated in an ATT plant based on the calorific values of the MSW streams.

IWMSs 9 and 10, where Mechanical Biological Treatment is included, provide the best environmental savings in terms of POCP, and IMSW 10 shows the lowest total burdens for ADP and HTP. By including additional sorting processes at the MBT plant, more materials are recycled and the RDF sent to the incineration plant will have a higher calorific value than the unsorted MSW. As a result, avoided burdens from the incineration of RDF are higher than from the combustion of MSW and account for 1.8 MJ of electricity and 4.8 MJ of heat per 1 kg of RDF being replaced by the UK grid electricity and heat.

Overall, IWMSs that use ATT as the primary waste treatment technology proved to be the best options with regards to the overall performance in all impact categories. Scenarios where landfill with a partial gas utilisation is used as the main treatment technology has the least environmental savings in most categories and significant environmental burdens in terms of GWP and EP compared to other integrated waste management systems evaluated in this project.

7.7.2. Life Cycle Assessment results – 'BAU' scenario.

Table 7.14 shows the total environmental impacts (direct and indirect burdens – avoided burdens) of the proposed integrated waste management systems (S1-10) for the BAU legacy scenario in 6 impact categories.

It can be noted that the results for the BAU legacy scenario show similar trends to those for the Games period in most impact categories. IWMSs where landfill is the primary treatment option have the highest environmental burdens in terms of GWP, EP and ADP. IWMSs 7 and 8, where ATT is the primary treatment option have the lowest environmental burdens in terms of GWP, AP and EP. It can be seen that the total GWP for IWMS 8 is negative. This is because the avoided burdens resulting from the substitution of the grid electricity and heat with the electricity and heat generated in the ATT facility are higher than direct and indirect burdens associated with the process.

Table 7. 14. Total environmental burdens (direct + indirect burdens – avoided burdens) for 10 IWMSs (S1-S10) for the BAU legacy scenario in 6 impact categories. High environmental burdens are highlighted in red, low environmental impacts and high avoided burdens are highlighted in green.

	GWP (t CO2 eq)	AP (kg SO2eq)	EP (kg Phosphate eq)	ADP (GJ)	POCP (kg Ethene eq)	HTP (t DCBeq)
S1	**14,515**	**-15,581**	**6,432**	**-77,796**	**403**	**-1,596**
S2	3,217	-21,123	-2,871	-137,418	-2,522	**-1,767**
S3	**13,831**	-17,576	**5,377**	**-84,877**	**554**	-2,764
S4	2,533	-23,118	**-3,925**	-144,499	-2,371	-2,935
S5	**17,927**	-17,046	**9,534**	-78,412	**923**	-2,747
S6	5,005	-25,460	**-4,079**	**-174,660**	-2,840	**-3,046**
S7	**513**	**-26,034**	-3,168	-148,159	-2,445	**-1,707**
S8	**-170**	**-28,029**	**-4,223**	-155,241	-2,294	-2,875
S9	3,041	**-14,195**	-204	-162,177	**-8,092**	-2,225
S10	2,304	**-16,343**	-1,340	**-169,802**	**-7,930**	**-3,482**

Figures 7.11 – 7.16 show direct and indirect burdens and avoided burdens for 1 year Legacy period for the BAU site design scenario for each of the 10 integrated waste management systems (S1-S10) in 6 impact categories.

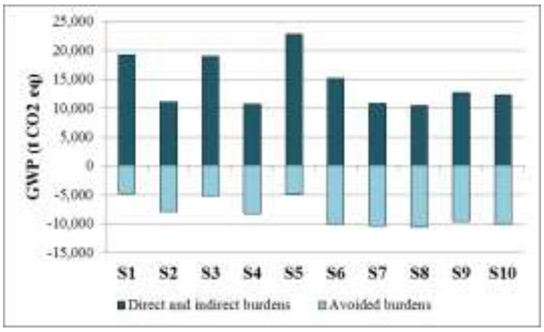


Figure 7. 11. GWP – BAU scenario.

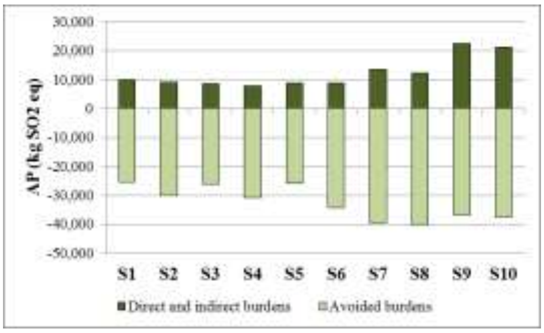


Figure 7. 12. AP – BAU scenario.

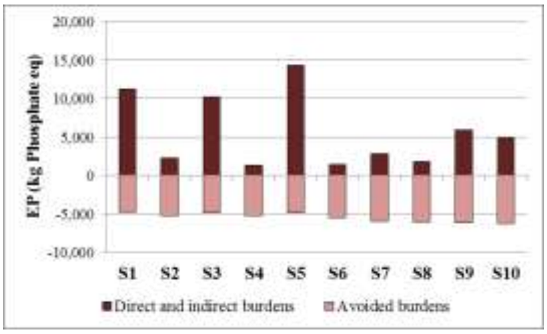


Figure 7. 13. EP – BAU scenario.

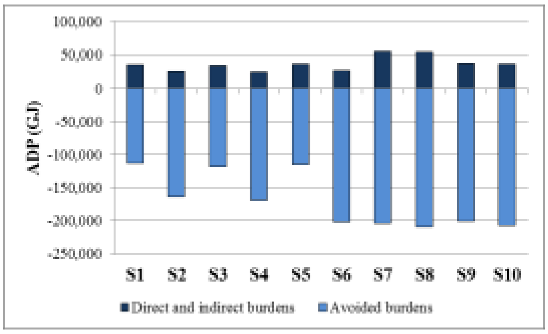


Figure 7. 14. ADP – BAU scenario.

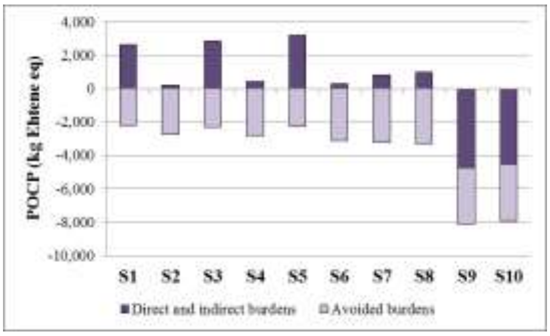


Figure 7. 15. POCP – BAU scenario.

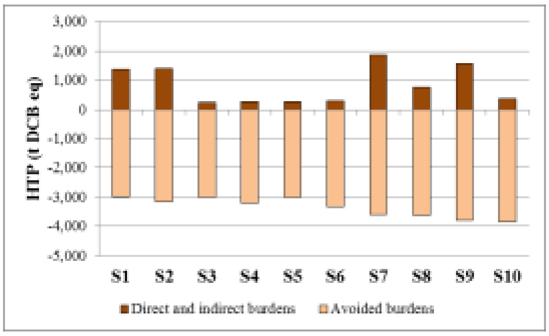


Figure 7. 16. HTP – BAU scenario.

IWMSs 9 and 10 have the highest environmental burdens in terms of AP. However, IWMS 10 has the highest environmental savings in terms of ADP, POCP and HTP. Although IWMS 6 has a significantly how GWP, it also has the highest environmental savings in terms of EP, ADP and HTP.

Generally, there is no a single IWMS that shows the best performance in all impact categories. However, it can be seen that IWMSs 7 and 8 have the lowest environmental burdens in all categories apart from HTP. IWMSs where landfill is the primary treatment option prove to have the worst environmental performance in most impact categories.

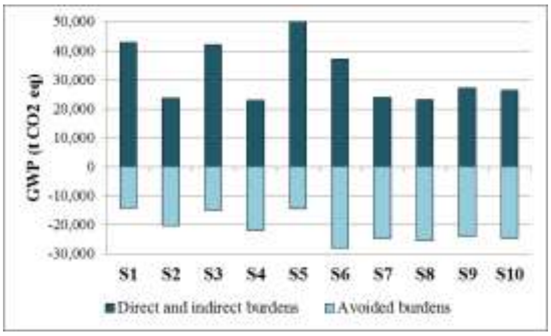
7.7.3. Life Cycle Assessment results – 'CW' scenario.

Table 7.15 shows the total environmental impacts (direct and indirect burdens – avoided burdens) of the proposed integrated waste management systems (S1-10) for the CW legacy scenario in 6 impact categories.

Table 7. 15. Total environmental burdens (direct + indirect burdens – avoided burdens) for 10 IWMSs (S1-S10) for the CW legacy scenario in 6 impact categories. High environmental burdens are highlighted in red, low environmental impacts and high avoided burdens are highlighted in green.

	GWP (t CO2 eq)	AP (kg SO2eq)	EP (kg Phosphate eq)	ADP (GJ)	POCP (kg Ethene eq)	HTP (t DCBeq)
S1	**28,622**	-54,876	**1,738**	**-280,239**	-1,244	-6,194
S2	3,469	-66,383	-14,924	-398,735	-7,474	-6,529
S3	**27,032**	-59,512	-713	-296,695	**-894**	-8,906
S4	959	**-36,234**	-8,865	-415,191	-3,634	**-4,715**
S5	**36,546**	-58,306	**8,940**	**-281,730**	**-27**	-8,867
S6	9,185	**-79,951**	**-17,926**	**-523,083**	-8,573	**-9,649**
S7	**-698**	-74,712	-15,064	-413,366	-7,016	-6,392
S8	**-2,285**	**-79,348**	**-17,515**	-429,822	-6,665	-9,106
S9	3,026	-53,228	-10,352	-453,989	**-18,640**	-7,875
S10	1,576	-57,461	-12,590	**-469,014**	**-18,320**	**-10,353**

Figures 7.17 – 7.22 show direct and indirect burdens and avoided burdens for 1 year Legacy period for the CW site design scenario for each of the 10 integrated waste management systems (S1-S10) in 6 impact categories.



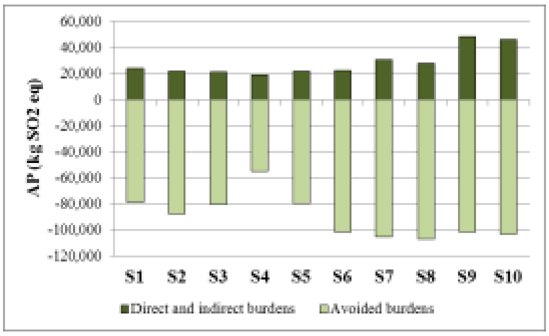
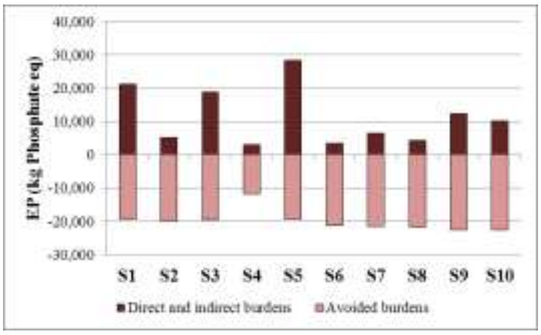


Figure 7. 17. GWP – CW scenario.

Figure 7. 18. AP – CW scenario.



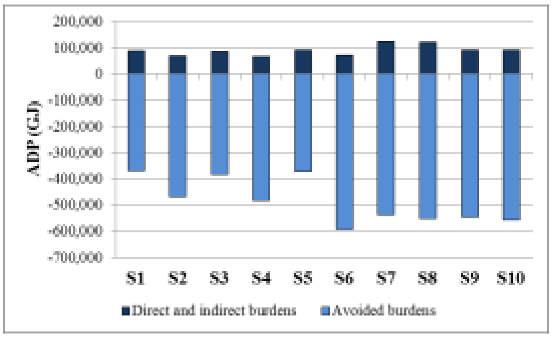
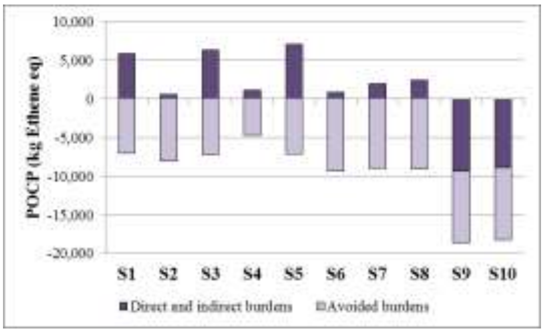


Figure 7. 19. EP – CW scenario.

Figure 7. 20. ADP – CW scenario.



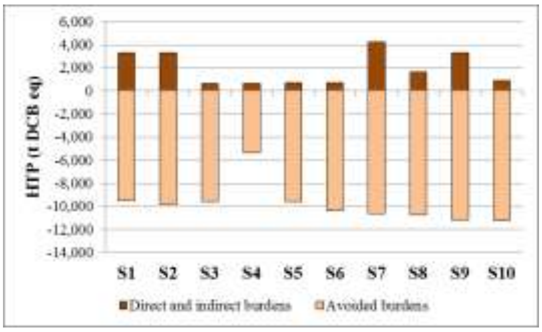


Figure 7. 21. POCP – CW scenario.

Figure 7. 22. HTP – CW scenario.

It is evident that for the CW scenario the trends are similar to those for the BAU scenario for most IWMSs. It can be seen that GWP for IWMSs 7 and 8, where ATT is a primary treatment technology, have negative total values which indicates the overall environmental savings. Also, it can be seen that these systems have significant environmental savings in most of the categories. IWMS 6 also indicates high environmental savings in term of AP, EP, ADP and POCP; however it has significant impact in terms of GWP.

Overall, the trends in most impact categories are very similar to the ones described for the BAU scenario. Although the composition of waste in the BAU scenario is different to the MSW composition in the CW scenario, as expected, the IWMSs with landfill as a primary waste treatment technology have the highest environmental impacts in most categories. IWMS 5 has the highest environmental performance of all the systems. This is due to the fact that no source-separated OFMSW is recovered and, thus, being sent to landfill.

7.7.4. Life Cycle Assessment results – 'HRHD' scenario.

Table 7.16 shows the total environmental impacts (direct and indirect burdens – avoided burdens) of the proposed integrated waste management systems (S1-10) for the CW legacy scenario in 6 impact categories.

Table 7. 16. Total environmental burdens (direct + indirect burdens – avoided burdens) for 10 IWMSs (S1-S10) for the HRHD legacy scenario in 6 impact categories. High environmental burdens are highlighted in red, low environmental impacts and high avoided burdens are highlighted in green.

	GWP (t CO2 eq)	AP (kg SO2eq)	EP (kg Phosphate eq)	ADP (GJ)	POCP (kg Ethene eq)	HTP (t DCBeq)
S1	**41,452**	**-55,452**	**13,502**	**-282,134**	**331**	**-6,023**
S2	7,594	-71,848	-12,346	-455,506	-8,314	-6,522
S3	**39,493**	-61,168	**10,480**	-302,421	**763**	-9,368
S4	5,635	-77,563	-15,367	-475,794	-7,883	-9,867
S5	**51,226**	-59,650	**22,388**	**-283,904**	**1,819**	-9,319
S6	13,595	**-86,234**	**-15,916**	**-583,467**	-9,428	**-10,269**
S7	**312**	-84,855	-12,977	-479,797	-7,915	**-6,328**
S8	**-1,646**	**-90,570**	**-15,999**	-500,084	-7,483	-9,673
S9	6,792	**-52,011**	-5,098	-523,556	**-24,039**	-7,988
S10	4,788	-57,859	-8,190	**-544,315**	**-23,597**	**-11,411**

Figures 7.23 – 7.24 show direct and indirect burdens and avoided burdens for 1 year Legacy period for the CW site design scenario for each of the 10 integrated waste management systems (S1-S10) in 6 impact categories.

The results provided in table 7.16 and figures 7.23-7.28 for the HRHD scenario follow the same trends as for the BAU and CW scenario. IWMSs with landfill as a primary technology show the worst environmental impacts. IWMS 5 has the highest environmental impacts in terms of GWP, EP, ADP and POCP, followed by IWMS 1 which is the second worst performing systems in all impact categories. The best systems in terms of GWP values are IWMSs 7 and 8 where ATT is the primary technology.

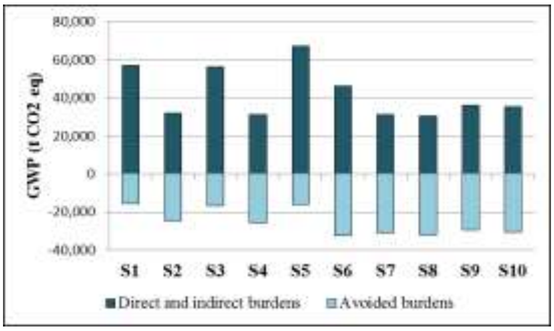


Figure 7. 23. GWP – HRHD scenario.

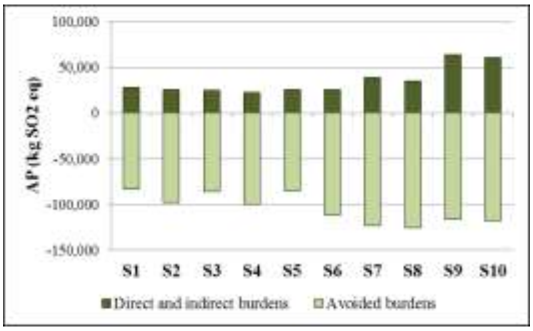


Figure 7. 24. AP – HRHD scenario.

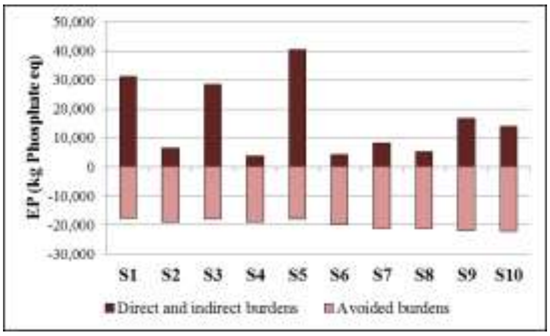


Figure 7. 25. EP – HRHD scenario.

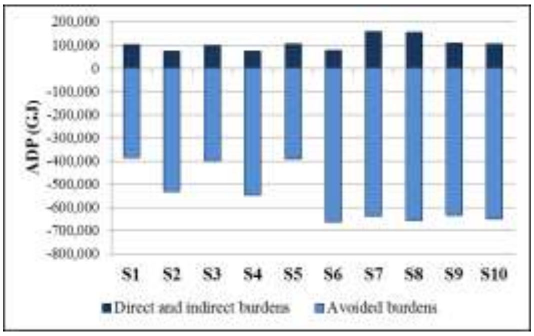


Figure7. 26. ADP – HRHD scenario.

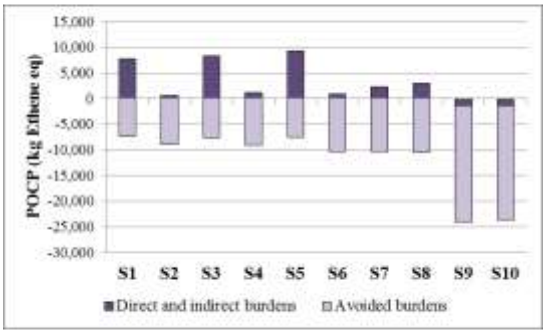


Figure 7. 27. POCP – HRHD scenario.

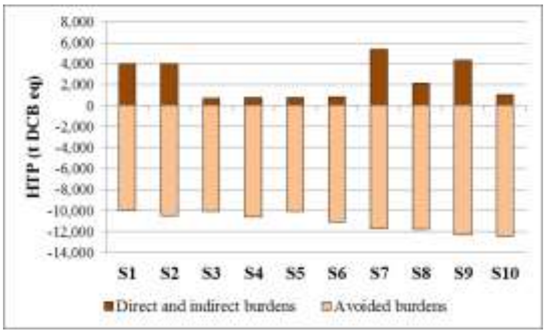


Figure 7. 28. HTP – HRHD scenario.

The results in sections 7.7.1 – 7.7.4 are provided in terms of the total environmental impact per functional units specified in section 7.5.2. Therefore, the higher quantity of the total MSW treated inevitably results in higher total environmental burdens. In order to identify which post-event scenario has the least environmental impact, section 7.7.5 provides the results of the environmental impacts per 1 tonne of MSW which allow a comparison between the post-event scenarios.

7.7.5. Overall LCA results for 10 IWMSs for all scenarios per 1 tonne of MSW.

A fair comparison of the environmental impacts based solely on the results provided in sections 7.7.1 - 7.7.4 is not possible because the FUs are different for all investigated scenarios. Therefore, in this section the LCA results are modified and presented for the same FU, which is 1 tonne of MSW. Table 7.17 provides the LCA results in all impact categories considered in this project for the event phase and all scenarios of the post-event legacy phase in regards to the environmental impacts resulting from the treatment of 1 tonne of MSW in 10 IWMSs examined in this project.

It can be seen that in regards to 1 tonne of MSW, the scenario ‘Commercial World’ shows the lowest environmental burdens in most impact categories considered in the this work. This can be explained by the fact that MSW generated in commercial buildings and communal facilities has higher quantities of recycling materials. Recycling rates in commercial buildings are also higher than in residential dwellings, which mean that more materials are recovered at the MRF and less MSW is being sent to waste treatment facilities. This, in turn, results in higher avoided burdens and total environmental savings.

The results in table 7.17 also point out the differences in values of environmental burdens for each of the proposed IWMSs. For example, it can be seen that IWMS 8 shows negative values for all post-event scenarios in terms of GWP which indicates environmental savings. However, this is not the same for the MSW produced during the Games. This can be explained by the fact that the MSW produced during the Games have different composition compared to the MSW produced in the post-event scenarios. First, 25% of the total MSW from the event venues is unsorted non-recyclable waste that goes directly to the incineration plant or landfill because it mainly consists of food and food packaging (RW, 2013). This value is considerably higher than in the typical residential and commercial buildings (table 7.3). Second, materials recovered at the MRF will mostly consist of paper and plastic. The highest environmental savings are achieved through the recovery of metals (table 7.8) and, therefore, credits for materials recovered at the MRF from the MSW during the

Games will be lower than those from the MSW produced in the post-event scenarios. In terms of other environmental impacts, the values for the Games period are similar to values for the post-event scenarios.

Table 7. 17. LCA results for 10 IWMSs for all scenarios per 1 tonne of MSW treated (the lowest environmental burdens or the highest environmental savings are highlighted in orange).

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
GWP (kg CO2 eq per tonne of waste)										
Games	935	337	930	332	993	696	220	217	306	300
Legacy										
BAU	916	203	873	160	1,131	316	32	-11	192	145
CW	759	92	717	50	969	244	-19	-61	80	42
HRHD	757	139	722	103	936	248	6	-30	124	87
AP (kg SO2 eq per tonne of waste)										
Games	-0.96	-1.25	-0.98	-1.26	-0.87	-0.87	-1.52	-1.53	-0.87	-0.89
Legacy										
BAU	-0.98	-1.33	-1.11	-1.46	-1.08	-1.61	-1.64	-1.77	-0.90	-1.03
CW	-1.46	-1.76	-1.58	-1.88	-1.55	-2.12	-1.98	-2.10	-1.41	-1.52
HRHD	-1.01	-1.31	-1.12	-1.42	-1.09	-1.58	-1.55	-1.65	-0.95	-1.06
EP (kg Phosphate eq per tonne of waste)										
Games	-0.06	-0.45	-0.07	-0.46	-0.02	-0.43	-0.46	-0.47	-0.34	-0.35
Legacy										
BAU	0.41	-0.18	0.34	-0.25	0.60	-0.26	-0.20	-0.27	-0.01	-0.08
CW	0.05	-0.40	-0.02	-0.46	0.24	-0.48	-0.40	-0.46	-0.27	-0.33
HRHD	0.25	-0.23	0.19	-0.28	0.41	-0.29	-0.24	-0.29	-0.09	-0.15
ADP (MJ per tonne of waste)										
Games	-3,331	-6,377	-3,389	-6,435	-2,846	-3,123	-7,114	-7,140	-6,966	-7,038
Legacy										
BAU	-4,910	-8,673	-5,357	-9,120	-4,949	-11,024	-9,351	-9,798	-10,236	-10,717
CW	-7,434	-10,577	-7,871	-11,014	-7,474	-13,876	-10,966	-11,402	-12,043	-12,442
HRHD	-5,154	-8,322	-5,525	-8,692	-5,187	-10,659	-8,765	-9,136	-9,565	-9,944
POCP (kg Ethene eq per tonne of waste)										
Games	-0.02	-0.17	-0.02	-0.17	-0.01	-0.13	-0.17	-0.16	-0.42	-0.41
Legacy										
BAU	0.03	-0.16	0.03	-0.15	0.06	-0.18	-0.15	-0.14	-0.51	-0.50
CW	-0.03	-0.20	-0.02	-0.19	0.00	-0.23	-0.19	-0.18	-0.49	-0.49
HRHD	0.01	-0.15	0.01	-0.14	0.03	-0.17	-0.14	-0.14	-0.44	-0.43
HTP (kg DCB eq per tonne of waste)										
Games	-171	-180	-180	-190	-176	-175	-177	-186	-193	-205
Legacy										
BAU	-101	-112	-174	-185	-173	-192	-108	-181	-140	-220
CW	-164	-173	-236	-245	-235	-256	-170	-242	-209	-275
HRHD	-110	-119	-171	-180	-170	-188	-116	-177	-146	-208

To identify which parts of the waste treatment processes considered in this project are the highest contributors of the environmental burdens or savings, a hot-spot analysis has been carried. The results of the analysis are examined in section 7.7.6.

7.7.6. Hot-spot analysis.

Figures 7.29 – 7.34 provide results of a hot-spot analysis of the different waste treatment processes (MRF, AD, Composting, EfW, Landfill, ATT) considered in the 10 scenarios analysed in this study in terms of GWP. The results are based on the waste quantities calculated for the BAU scenario. A hot-spot analysis highlights the relevant importance of the avoided emissions for electricity and heat production, nutrients and materials recovery compared to the direct process and transport emission. As explained earlier, positive values mean environmental burdens and negative values represent environmental savings, or avoided burdens.

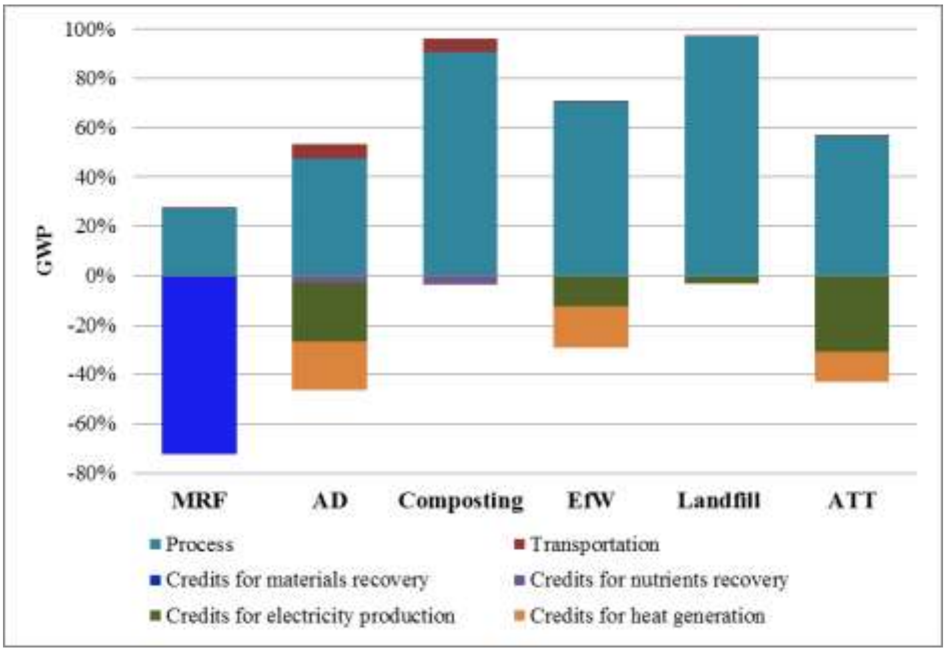


Figure 7. 29. Hot-spot analysis of the waste treatment processes – Global Warming Potential.

From figure 7.29 it can be seen that GHG emissions associated with the landfill process account for almost 100% of the total emissions. In this case, emissions arising from the transportation of waste are negligible due to the estimated transportation distances between waste treatment facilities and waste generation points. Avoided emissions from the electricity generation account for less than 2% of the total emissions.

The composting process shows similar results where most GHG emissions result from the process itself (mainly decomposition of the organic matter), and avoided burdens account only for approximately 2% of the total emissions due to the substitution of chemical fertiliser with recovered nutrients. Transport emissions contribute to almost 5% of the total emissions and are related to the transportation of organic waste to the composting facility and to the transportation and spreading of compost on arable lands.

GHG emissions directly resulting from the incineration and ATT processes are 70 and 58% respectively. Avoided emissions are significantly higher for the two thermal technologies compared to landfill due to higher credits for production of electricity and heat.

AD technology has high environmental savings in terms of GWP thanks to the emission credits for the substitution of recovered electricity and heat, and substitution of chemical fertiliser with recovered nutrients from the digestate. GHG emissions associated with transportation of waste and spreading of the digestate on the arable land are similar to those for the composting process.

MRF illustrates the highest environmental savings in terms of GWP (approximately 70%) due to the emission credits for substitution of virgin materials with recycled ones. This is in line with the outcomes of other LCA studies which prove that recycling results in higher environmental savings than other waste treatment options (Bovea et al., 2010; Slagstad and Brattebø, 2012; Mendes et al., 2004).

Figures 7.30 – 7.34 provide the results of the hot-spot analysis for other 5 impact categories considered in this work. In terms of AD (figure 7.30), the most significant environmental savings result from the MRF followed by the incineration and ATT plants. It can be seen that in EfW and ATT facilities more than 60% of the total impact is attributed to the credits for the production of electricity. It can be seen that almost 40% of the process emissions in landfill are attributed to the avoided emissions associated with the credits for the production of electricity, which is much higher value than in terms of the GWP.

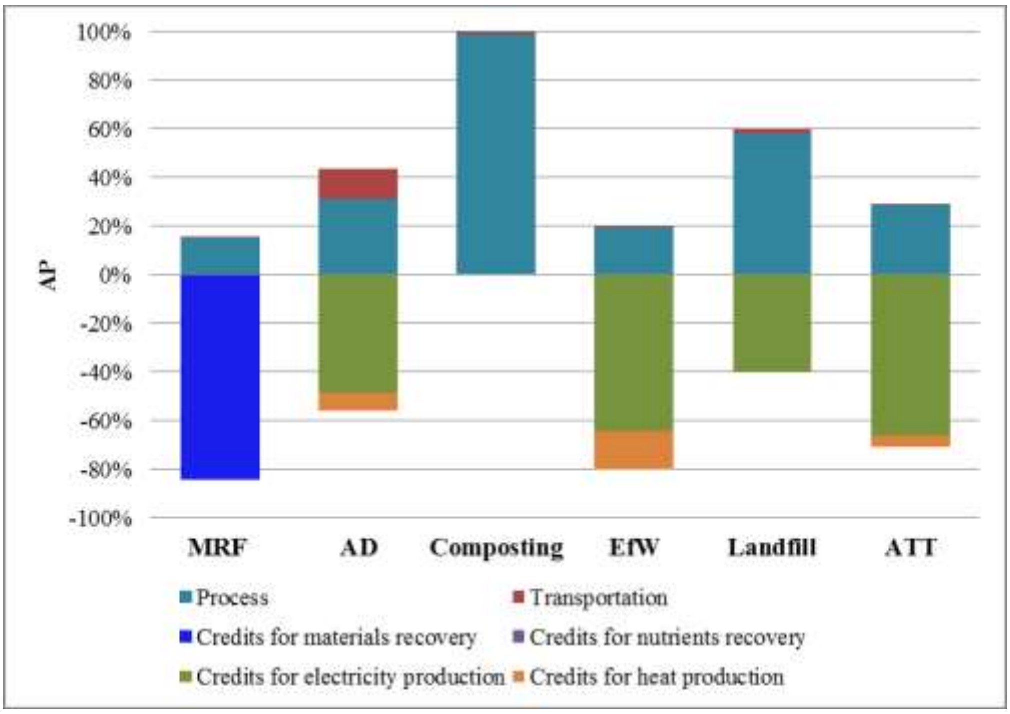


Figure 7. 30. Hot-spot analysis of the waste treatment processes – Acidification Potential.

Regarding the EP, avoided emissions resulting from the substitution of recycled materials constitute for more than 95% of the total emissions from the MRF. Avoided emissions due to the credits for electricity production are the highest for ATT (57%) followed by the EfW (43%) and AD (22%). Credits for electricity production in landfill are almost negligible.

In terms of the ADP, EfW facility indicates the total highest avoided burdens resulting from the credits for both electricity and heat production (98%) due to the highest credits for heat production amongst all the processes. The highest credits for electricity production in terms of ADP result in the ATT plant followed by the AD and landfill. MRF shows high environmental savings due to the credits for materials recovery.

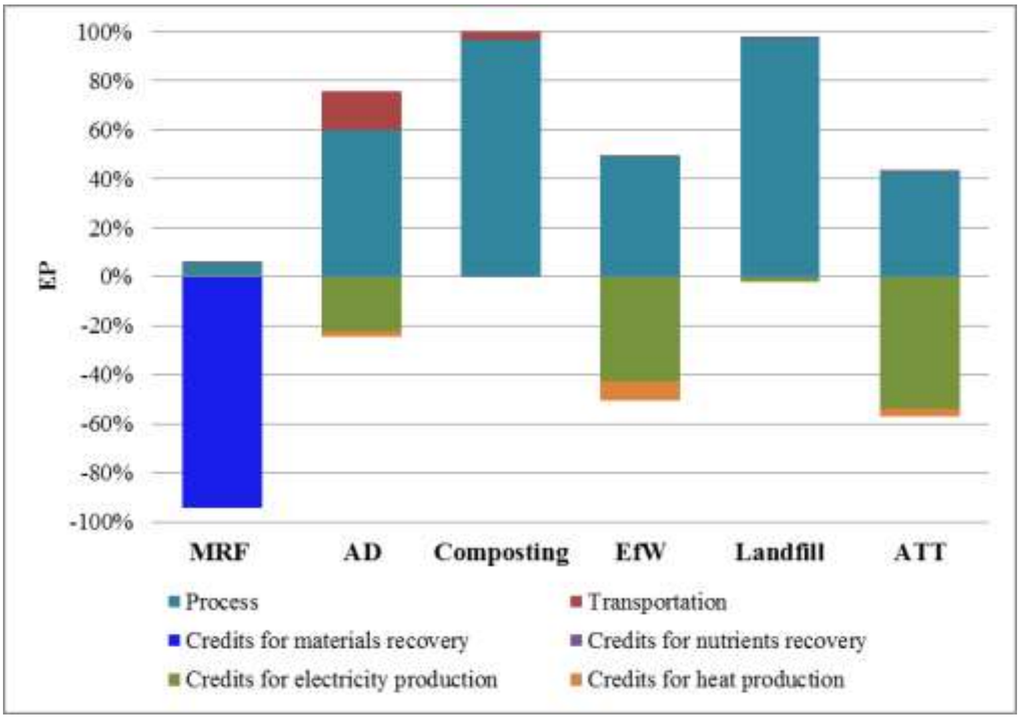


Figure 7. 31. Hot-spot analysis of the waste treatment processes – Eutrophication Potential.

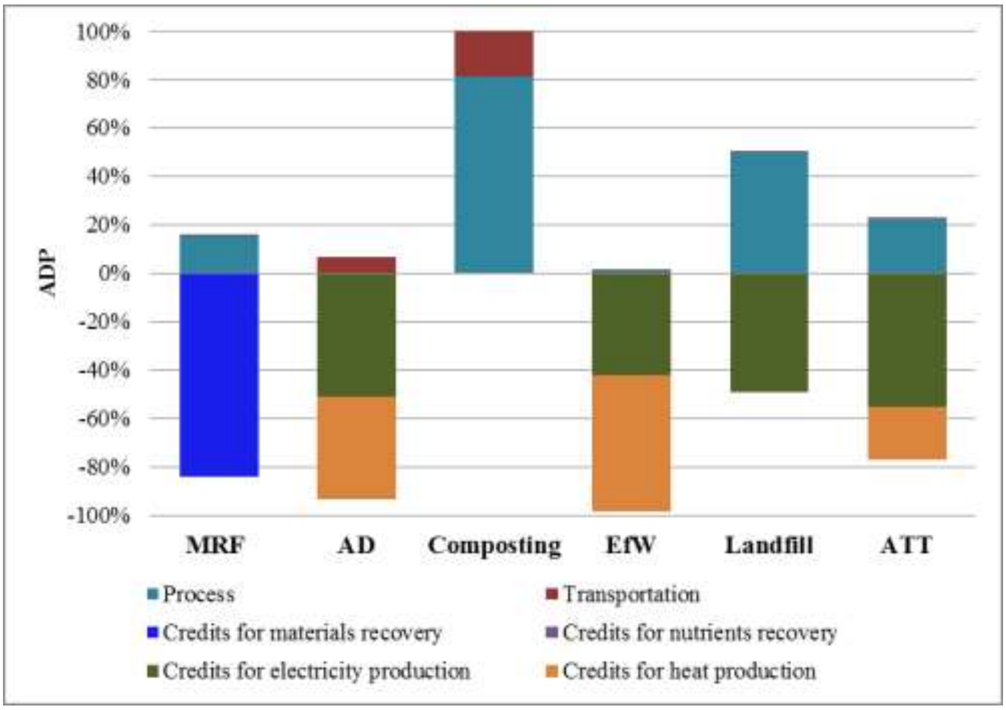


Figure 7. 32. Hot-spot analysis of the waste treatment processes – Abiotic Depletion Potential.

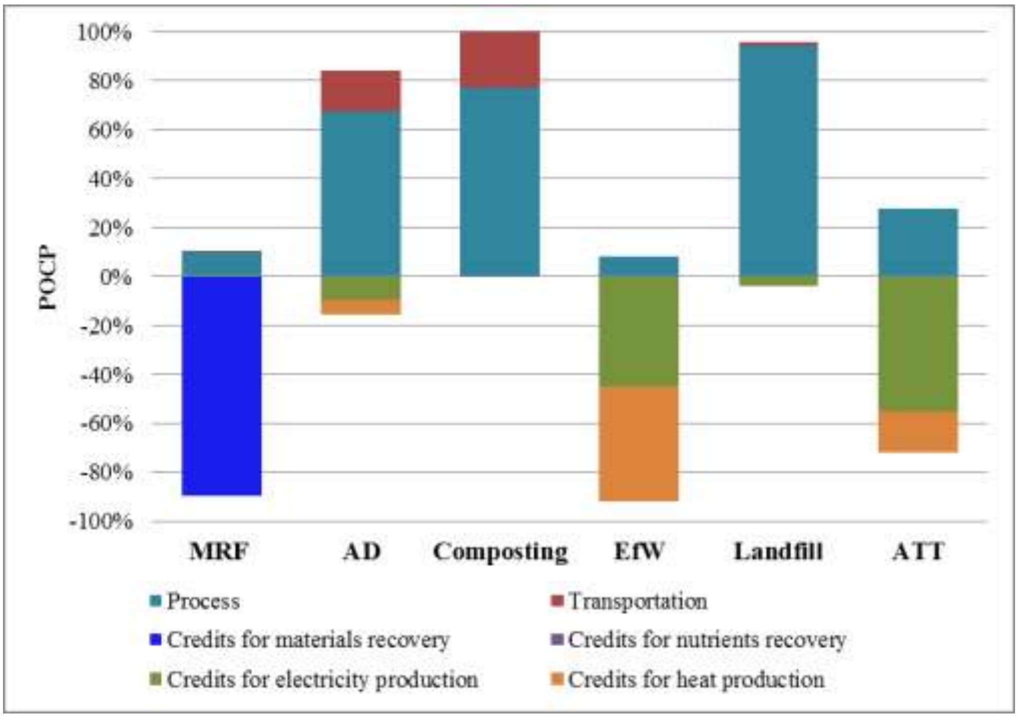


Figure 7. 33. Hot-spot analysis of the waste treatment processes – Photochemical Ozone Creation Potential.

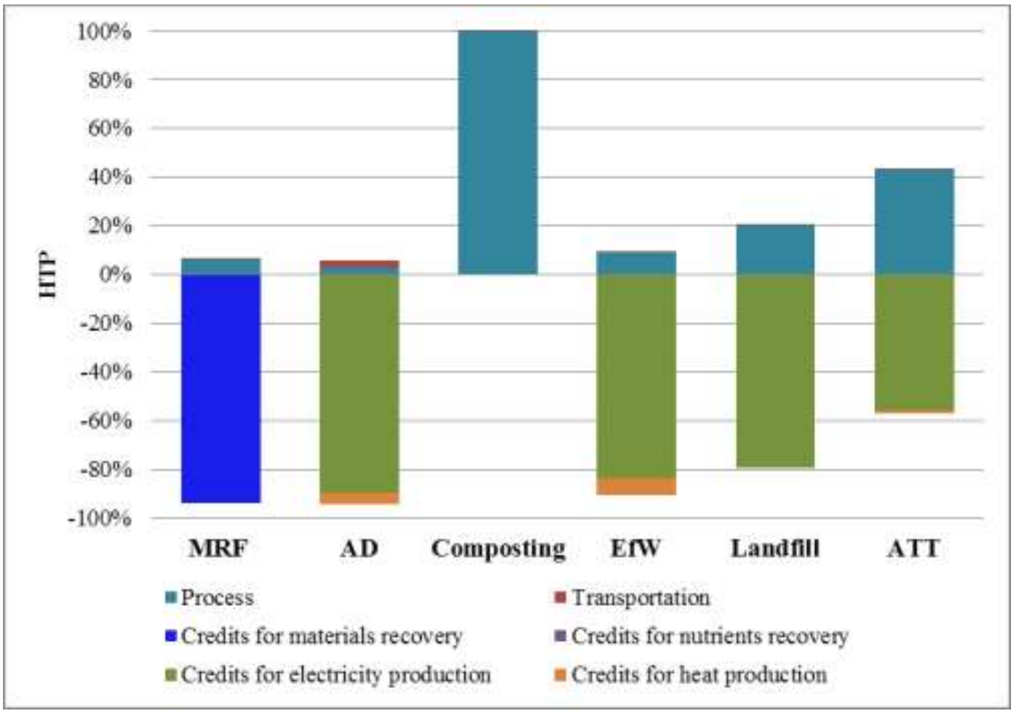


Figure 7. 34. Hot-spot analysis of the waste treatment processes – Human Toxicity Potential.

EfW shows the highest avoided burdens due to the credits for electricity and heat production in terms of POCP followed by the MRF process where the highest burdens result from the credits for material recovery. High avoided burdens in ATT mostly result due to the credits for electricity production. AD, composting and landfill result in the positive total POCP values, which means that the avoided burdens for energy credits are much smaller than the overall process emissions.

In regard to the HTP, MRF and AD show the highest avoided burdens followed by the EfW, landfill and ATT processes. It can be seen that the most avoided burdens in AD, EfW, landfill and ATT processes are attributed to the credits for the electricity production.

It has to be noted that the credits for nutrients recovery in AD and composting processes are only calculated in terms of GWP due to the availability of data expressed only in terms of GHG emissions. Therefore, it can be seen that no avoided burdens are associated with composting process apart from those calculated in terms of GWP.

Overall, the MRF process has the highest environmental savings in all impact categories due to the credits for recovered materials. This is explained by the fact recycled materials can replace virgin materials and, therefore, save energy and raw materials.

Thus, a sensitivity analysis has been carried out to evaluate to what extent further environmental savings could be achieved if recycling rates increased and the waste composition varied in terms of recyclable content (i.e. paper and plastic).

7.7.7. Sensitivity analysis.

In order to understand how the overall results of the model are affected by changes in certain parameters, two sensitivity analyses were carried out. Figure 7.35 provides the results of a sensitivity analysis for the IWMS 1 for the BAU scenario where the results of changes in the recycling rates have been investigated.

Recycling rates were first reduced by 5, 10 and 15% compared to the baseline scenario, and then increased by the same values. Recycling rates may fluctuate due to variations in the daily composition of MSW, different operating conditions at various recycling facilities, and different recycling schemes. Therefore, it is one of the parameters that can significantly affect the results of the overall integrated waste management system.

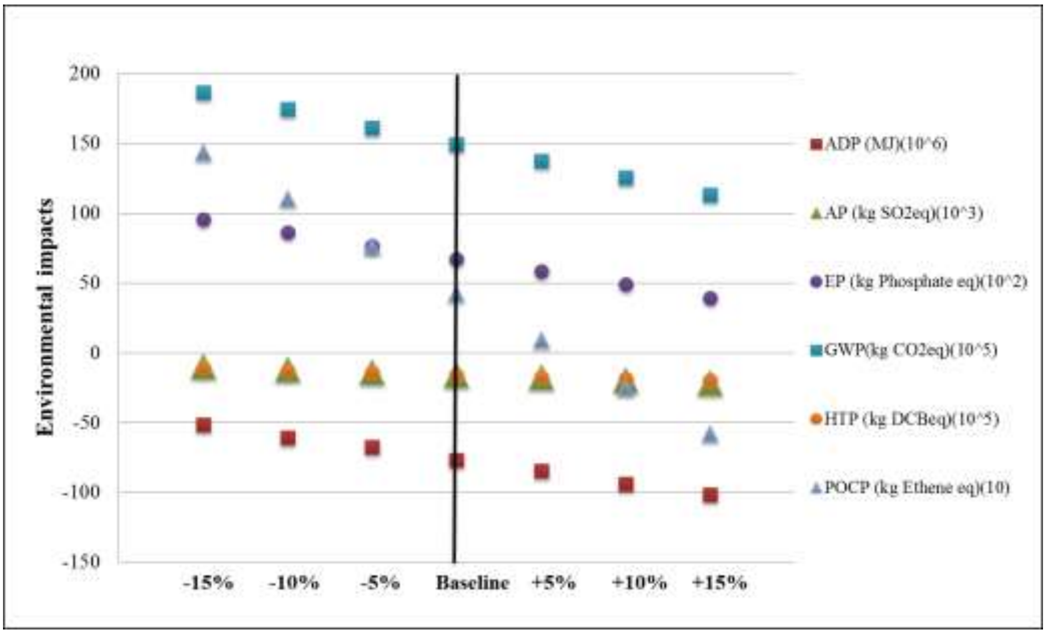


Figure 7. 35. Sensitivity Analysis for IWMS 1 for BAU scenario - changes in recycling rates (+/- 5, 10, 15% of the average recycling rates applied in the current study).

It can be seen that an increase in the recycling rate results in improved environmental performance in all impact categories. In particular, the performance improves dramatically in categories such as POCP and GWP. For example, an increase of all recycling rates by 15% results in almost 100% reduction in POCP. On the opposite, a reduction of recycling rates by 15% doubles the amount of POCP compared to the baseline scenario. In terms of GWP, increasing the recycling rate by 10% reduces the GWP by 17% and increasing the recycling rate by 15% results in almost a 30% decrease of the GWP.

AP, and HTP are the impact categories that seem to be the least affected by changes in recycling rates.

Figure 7.36 provides the results of the sensitivity analysis of IWMS 1 for the BAU scenario where the effects of changes in MSW composition on the overall results have been examined.

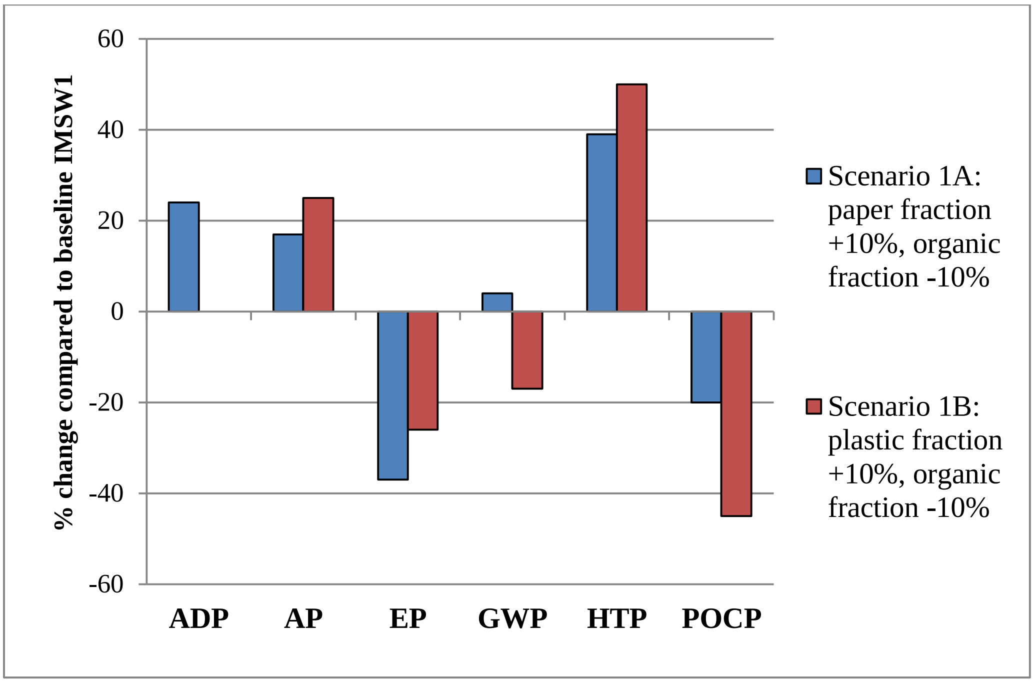


Figure 7. 36. Sensitivity Analysis for for IWMS 1 for BAU scenario - changes in MSW composition - recyclable fractions.

MSW is not a homogenous substance; the amount of various materials in a total waste stream may vary considerably depending on a number of factors such as seasonal variations of food consumption, recycling habits of residents in different areas and many others. Organic fractions are of the most importance as they can be treated by various technologies, sometimes with significant amounts of recovered energy due to their high caloric values. Thus, it is important to be able to estimate how changes in various waste fractions affect the overall results of the waste system.

In Scenario 1A, the total paper fraction of waste was increased by 10% and the total organic fraction was reduced by 10% compared to the baseline values of scenario1. From Figure 15 it can be seen that the environmental burdens increased in all impact categories, except EP and POCP, as a result of these changes. The value for HTP increased by almost 40%, for ADP the increase resulted in approximately 20%. GWP is the least affected.

In Scenario 1B, the total plastic fraction of MSW was increased by 10% and the total organic fraction was reduced by 10% compared to the baseline values of scenario1. It can be seen that the ADP category is the only impact category that was not affected by the changes in waste composition. HTP increased by almost 50% and AP increased by almost 20%. POCP and EP have the similar trends to the ones in Scenario 1A, with POCP being reduced by more than 40% and EP being reduced by more than 20%.

7.8. Summary.

This chapter provides the results of the environmental assessment of 10 integrated waste management systems for event period and three potential legacy design scenarios of the London Olympic Park. The assessment was carried out applying the LCA methodology with system expansion using GaBi Product Sustainability Software (GaBi, 2013).

The outcomes of the environmental evaluation of the IWMSs provide crucial information to decision makers when planning the long-term waste management solutions. The LCA results can assist decision making process by answering the questions framed in the beginning of this chapter:

1. Which legacy scenario is the optimum in terms of the lowest environmental burdens?
2. What waste treatment facilities can provide the best long-term solution and why?

The results of the current study demonstrate that although the 'Business as Usual' legacy scenario may be a preferred option by the government, the best environmental solution from the viewpoint of the integrated waste management system is the 'Commercial World' scenario. In this case, the results show it has the lowest environmental burdens in all impact categories for all IWMSs examined in this work.

The LCA results also show that the most significant environmental savings in all IWMSs considered in this study are achieved through materials recycling at the MRF and through energy recovery from AD, EfW and ATT plants. This is evident from the results which show that GWP is the lowest in the two integrated waste management systems where ATT is the main technology; ADP is the lowest in those ones where incineration with energy recovery is used; POCP is the lowest where

MBT is combined with other treatment facilities. To further highlight this, the results of a hot-spot analysis show that the avoided burdens from the MRF are almost three times higher than direct and indirect burdens, which indicate significant environmental savings resulting from the recycling process. A sensitivity analysis illustrates how the environmental benefits can be improved further by increasing the recycling rates. Thus, the analysis shows that a combination of facilities including MRF, MBT, ATT and incineration with energy recovery plants should be part of the long-term city development plan for the legacy of the London Olympic Park as they provide the best environmental solutions.

It is clear that there is no a single waste management system that performs best in all impact categories. Moreover, in order to carry out a complete sustainability assessment, many other issues need to be taken into consideration. First of all, an economic evaluation of each IWMS has to be carried out. A cost-benefit analysis is normally applied in order to identify the economic feasibility of a proposed project. Second, social implications of the proposed waste treatment facilities have to be considered. Planning of a new waste treatment facility requires participation of all stakeholder groups, therefore open consultations and workshops have to be arranged. Stakeholders' viewpoints can be collected through surveys and the results can be quantified and analysed using MCDA technique as described in Chapter 4.

The overall outcome of the sustainability assessment of the proposed IWMSs will provide a holistic view of the proposed scenarios in terms of their economic, environmental and social impacts. Thus, the results will provide decision-makers with crucial information required for the long-term planning of mega-event projects including sustainable options for waste management, which were presented in this chapter.

Chapter 8. Conclusions and future work.

This chapter summarises the main findings of this work and presents the overall conclusions. The final section provides recommendations and directions for future work.

8.1. Conclusions.

Mega-event projects such as the Olympic Games or FIFA World Cup have significant effects on the host cities. These long-term multi-billion dollar projects change the look of the city through major regeneration projects and the development of the infrastructure and built environment. Moreover, they create long-lasting legacies that last for decades. Post-event legacies can be positive or negative. Decision makers face a difficult challenge of a complex planning of multiple phases of mega-event projects: from the design of the event site to the redevelopment and integration of the post-event site with the neighboring areas. Moreover, decision makers have to evaluate the environmental, economic and social impacts of the proposed design scenarios in order to determine the optimum solution.

A critical literature review presented in Chapters 2 and 3 of this thesis revealed several studies which attempted to investigate and quantify various impacts of mega-events. Most of the studies, however, address only the construction and event phases without the consideration of the post-event legacy phase. Only a few studies refer to legacy but mostly regarding the influence of a mega-event on tourism and promotion of sport in the host city. Therefore, it was identified that there is no a systematic framework that can be applicable for the thorough sustainability assessment of all phases of a mega-event project.

In this context, the main objective of this work was to develop a comprehensive methodology that can assist decision makers with the evaluation of different design scenarios in order to identify the optimum solution. A proposed novel methodology for the holistic assessment of mega-event projects was presented in Chapter 4 of this thesis. Although the methodology addresses all steps of the planning process, the focus of this work is on the social and environmental assessment. A case study based on the London Olympic Park was applied to test the feasibility of the proposed framework.

Mega-event projects affect many stakeholders and, therefore, planning process should be carried out with participation of all stakeholder groups. Stakeholders' engagement in the planning of mega-event projects can be in the form of workshops, advisory committees or other public meetings. In order to identify the views of different stakeholders on certain aspects, surveys are normally distributed at such meetings. However, such surveys often comprise qualitative questions and their results are hard to analyse and compare. In Chapter 5 of this thesis it was demonstrated how a MCDA tool can be used to quantify the results of the surveys. A sample survey was developed and distributed amongst a group of students and academics at UCL who represented 5 different stakeholders groups. They had to apply different weights to different criteria according to their preference. The results were analysed and presented in a graphical form for easy interpretation. The outcomes of such surveys present valuable information regarding the views of stakeholders on different social aspects and design features. This information can be used by the decision makers during the planning of the event and the post-event site venues and infrastructure.

Chapters 6 and 7 of this thesis provided the results of the environmental assessment of the whole life cycle of a mega-event project. To test the robustness of the methodology, three post-event site design scenarios of the London Olympic Park were developed. The environmental assessment of the mega-event project was carried out using a series of the optimisation models presented in Chapter 6 and a series of LCA models described in Chapter 7.

Optimisation models were developed in order to estimate and optimise the GHG emissions associated with the transportation, energy, water and materials used at each phase of the project for three scenarios: Business as Usual, Commercial World and High Rise High Density. The results of the models demonstrated that the highest emissions are attributed to the legacy phase in all scenarios, particularly to the transportation of visitors and embodied carbon from the construction materials. The models can be used by the decision makers to estimate the environmental impacts of the proposed design scenarios, identify which parameters have the highest effects on the overall results, and determine the optimum settings in terms of the lowest environmental impacts. Although the optimum scenario can be considered a theoretical optimum and cannot be implemented in practice, it can serve as a useful performance benchmark during the planning process.

A set of the LCA models described in Chapter 7 was developed to evaluate the integrated waste management systems proposed for MSW treatment during the event and post-event phases of the project. 10 complex IWMSs were elaborated to reflect the current and future UK waste management strategies. The total environmental burdens of the IWMSs were determined for the event period and proposed post-event site design scenarios. The LCA results and the results of the hot-spot analysis demonstrated that the highest environmental savings occur due to the materials recycling and the CW scenario has the lowest environmental impacts in terms of treating 1 tonne of waste. The results of the sensitivity analysis demonstrated how changes in the recycling rates and waste composition affect the overall results.

The novel assessment framework presented in this work is an upper-tier tool that can be used by decision makers during the planning of a mega-event project. Decision makers include the event's Organising Committees, local authorities, potential investors and urban planners. They can apply the methodology as early as the bidding stage to identify the economic, environmental and social impacts of various design scenarios, consider the trade-offs between different aspects and determine the optimum solution. Due to the long-term impacts of mega-events on the host cities, organising committees now require the event organisers not only to develop the sustainability strategy for the actual event but also to produce a comprehensive post-event performance reports. A proposed framework is a tool that can assist decision makers with the holistic impact assessment of different stages of the project, setting up performance benchmarks, optimising the scenarios and monitoring the progress. This framework can also be applied to other projects. For example, local authorities can use it to estimate the impacts of various infrastructure projects or urban planners can apply it for the impact assessment of the regeneration projects.

The application of the proposed framework to a case study of the London Olympic Park proved that most impacts occur in the legacy phase. This emphasises the significance of the comprehensive evaluation and optimisation of the proposed post-event design scenarios at the early stages of the project. However, although the results of the environmental assessment present valuable information to decision makers, the final decision on the implementation of the specific scenario depends on many other factors such as the economic costs and social and cultural impacts. In Chapter 7 it was identified that the CW scenario is the best environmental solution in terms of waste management. The results provided in Chapter 6 show that the BAU scenario has the lowest total GHG emissions for the whole project life cycle. It can be seen that the proposed methodology can greatly assist in the planning process and help decision makers with the quantitative results of the evaluation and optimisation of the environmental impacts of the proposed scenarios. However, planning of mega-event projects is still a very complex task which requires consideration of many various aspects and, therefore, it is up to the decision makers and stakeholders to agree on the ultimate optimum solution.

8.2. Future work.

Due to the scope of this project, only the complete environmental assessment was carried out for a case study of the London Olympic Park. Therefore, comprehensive social and economic assessments are necessary for the holistic sustainability assessment as described in the proposed framework.

In this work it was demonstrated how MCDA can be applied to analyse and quantify the results of the social surveys. A short questionnaire was developed and distributed amongst a set of 'actors' to identify the views of different stakeholder groups on certain post-event site design features. A complete social assessment of the real mega-event project is a complex multi-phase task which needs participation of social scientists in order to produce comprehensive surveys, conduct stakeholders' interviews and help decision makers with analysing the results.

A thorough economic assessment is also a complicated task, particularly the estimation of the economic impacts of the proposed post-event scenarios. Mega-event projects entail complex private-public investment schemes and a large number of uncertainties due to the long-term nature of the legacy phase. Thus, full economic assessment should be carried out by the economists who can identify all significant features and tools required for this task.

A proposed methodology was applied to one case study - the London Olympic Park. However, it was applied to the past event and, therefore the focus of this work was on the assessment of the proposed legacy scenarios. It would be useful to apply a methodology at the early planning of the event site for another mega-event, such as the Tokyo 2020 Olympic Games. The results could provide decision makers with essential information on the whole life cycle impact assessment of different design scenarios and help with the planning process. A systematic application of the framework to a certain group of mega-events such as the Summer Olympic Games can help to determine specific performance benchmarks in different areas, optimise potential scenarios and monitor the progress in the post-event legacy phase.

The environmental impacts in Chapter 6 refer only to the GHG emissions, which is the most common measure of the environmental performance. It would be useful to include other emissions in the calculations, such as particulate matters (PM) or heavy metals emissions to water and land to determine other environmental impacts. At present, the availability of such data is very limited and reliability of data is often uncertain due to varying measuring tools and reporting techniques.

Finally, the optimisation models could be expanded into a multi-optimisation model which includes quantitative economic and social indicators. The results of the multi-objective optimisation model will provide a 3-dimentional non-inferior Pareto set which can be used by decision makers. As mentioned earlier, this will require contribution of social scientists and economists in order to develop a complete set of indicators and identify complex relationships between them.

Nomenclature.

AD – anaerobic digestion

ADP – abiotic depletion potential

AHP – analytical hierarchy process

AP – acidification potential

APC – air pollution control

ATT – advanced thermal treatment

BAU – business as usual

BS – British standard

CBA – cost-benefit analysis

CERES – Coalition for Environmentally Responsible Economics

CHP – combined heat and power

CPI – Consumer Price Index

COD – chemical oxygen demand

CW – commercial world

DCF – discounted cash flow

DECC – Department of Energy and Climate Change

DER – distributed energy resource

DFSIR – driving force-pressure-state-impact-response

E – economic

EA – energy/exergy analysis

EEA – European Environmental Agency

EF – Ecological Footprint

EFA – ecological footprint analysis

EfW – energy from waste

EIA – environmental impact assessment

EIS – environmental impact statement

EN - environmental

EP – eutrophication potential

ESI – Environmental Sustainability Index

EU – European Union

EU-EMAS – European Eco-Management and Audit Scheme

EWI – Ecosystem Well-being Index

FU – functional unit

GAMS – General Algebraic Modelling System

GDP – Gross Domestic Product

GHG – greenhouse gas

GNP – Gross National Product

GPI – Genuine Progress Indicator

GRI – Global Reporting Initiative

GWP – global warming potential

HTP – human toxicity potential

HRHD – high rise, high density

HWI – Human Well-being Index

ICE – inventory of carbon and energy

IChemE – Institution of Chemical Engineers

ISEW – Index of Sustainable Economic Welfare

IWMS – integrated waste management system

IOC – International Olympic Committee

IPP – Integrated Product Policy

IPPC – Integrated Pollution Prevention and Control

ISO – International Organisation for Standardisation

LA21 – Local Agendas 21

LCA – life cycle assessment

LCIA – life cycle impact assessment

LEED – Leadership in Energy & Environmental Design

LHV – low calorific value

LLDC – the London Legacy Development Corporation

LOCOG – The London 2012 Olympic Games Organising Committee

LP – linear programming

MBT – mechanical biological treatment

MCDA – multi-criteria decision analysis

MEF – Measure of Economic Welfare

MFA – material flow analysis

MILP – mixed integer linear programming

MINLP – mixed integer non-linear programming

MIP – mixed integer optimisation problem

MO – multi-objective

MRF – materials recovery facility

MSW – municipal solid waste

NLP – non-linear programming

NMVOC – non-methanic volatile organic compound

NPV – net present value

OC – Organising Committee

OCOG – The Organising Committee for the Olympic Games

ODA – The Olympic Delivery Authority

OECD – The Organisation for Economic Cooperation and Development

OFMSW – organic fraction of municipal solid waste

PED – primary energy demand

PM – particulate matter

POCP – photochemical ozone creation potential

PRS – pressure-state-response

PV – present value

PV – photovoltaics

RA – risk analysis

RDF – refuse derived fuel

S - social

SA – sustainability assessment

SD – sustainable development

SEA – strategic environmental assessment

SET – social exchange theory

SI – sustainability indicator

SNA – system of national accounts

SPI – Sustainable Process Index

TBL – triple bottom line

TS – total solids

UCL – University College London

UK – United Kingdom

UNCCD – United Nations Convention to Combat Desertification

UNCSD – United Nations Commission on Sustainable Development

UNEP – United Nations Environmental Programme

VOC – volatile organic compound

WBI – Well-being Index

WPM – weighted product method

WSM – weighted sum method

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Appendices.

Appendix 1. Resource and materials usage data.

Table A1. Energy consumption in residential and non-residential buildings.

	Electricity consumption	Gas consumption	Unit	Reference
Residential dwellings:				
Detached house	4,500	18,000	kWh/year	DECC, 2013b
Semi-detached house	3,600	13,900	kWh/year	DECC, 2013b
End terrace house	3,400	12,500	kWh/year	DECC, 2013b
Mid terrace house	3,200	11,600	kWh/year	DECC, 2013b
Bungalow	3,100	13,200	kWh/year	DECC, 2013b
Flat (converted)	2,700	8,900	kWh/year	DECC, 2013b
Flat (purpose built)	2,500	7,100	kWh/year	DECC, 2013b
Offices:				
Type 1. Naturally ventilated cellular	54	151	kWh/m^2/year	ECG19, 2000
Type 2. Naturally ventilated open-plan	85	151	kWh/m^2/year	ECG19, 2000
Type 3. Air-conditioned, standard	226	178	kWh/m^2/year	ECG19, 2000
Type 4. Air-conditioned, prestige	358	210	kWh/m^2/year	ECG19, 2000
Retail:				
Average UK supermarket	1,500	250	kWh/m^2/year	Tassou et al., 2011.
Schools and nurseries:				
Primary schools and nurseries	43	139	kWh/m^2/year	Hong, S-M et al., 2013
Secondary schools	51	136	kWh/m^2/year	Hong, S-M et al., 2013
Restaurants and bars:				
Restaurant with bar	219	511	kWh/m^2/year	CIBSE, 2012

Restaurants in public house	450	1,050	kWh/m^2/year	CIBSE, 2012
Fast food outlet	267	623	kWh/m^2/year	CIBSE, 2012
Hospitals and medical centres:				
Hospital	471	314	kWh/m^2/year	Pérez-Lombard et al., 2007
Medical centre	44	104	kWh/m^2/year	EMSL, 2009.
Hotels:				
Budget hotel	150	160	kWh/m^2/year	HES, 2011, Bohdanowicz and Martinac, 2007
Luxury 4/5 star hotel	160	180	kWh/m^2/year	HES, 2011, Bohdanowicz and Martinac, 2007
Regular sports venues:				
Leisure pool centre	258	1321	kWh/m^2/year	ECG78, 2001
Fitness centre	194	449	kWh/m^2/year	ECG78, 2001
Olympic sports venues:				
Olympic Stadium	31169	24,349	kWh/day	London2012, 2010
Aquatic Centre	19,481	16,970	kWh/day	London2012, 2010
Hockey Centre	12,987	7,378	kWh/day	London2012, 2010
Velodrome	11,039	5,903	kWh/day	London2012, 2010
Basketball Arena	14,286	8,854	kWh/day	London2012, 2010
Handball Arena	11,688	6,641	kWh/day	London2012, 2010
Fencing Arena	11,039	5,903	kWh/day	London2012, 2010
IBC	64,935	29,513	kWh/day	London2012, 2010
MPC	16,234	11,068	kWh/day	London2012, 2010
Cauldron	0	9,464	kWh/day	London2012, 2010

Table A2. Water consumption in residential and non-residential buildings.

Building type	Daily demand	Unit	Occupancy	Reference
Residential dwellings:				
Detached house (4 bedrooms)	145	litres per person	3.2 person	ODA, 2011
Semi-detached house (3 bedrooms)	158	litres per person	2.6 person	ODA, 2011
End terrace house (2 bedrooms)	176	litres per person	1.9 person	ODA, 2011
Mid terrace house (2 bedrooms)	176	litres per person	1.9 person	ODA, 2011
Bungalow (3 bedrooms)	158	litres per person	2.6 person	ODA, 2011
Flat (converted) (2 bedrooms)	179	litres per person	1.8 person	ODA, 2011
Flat (purpose built)	197	litres per person	1.3 person	ODA, 2011
Offices:				
Offices with canteen	2.25	litre/m^2	-	ODA, 2011
Offices without canteen	2.1	litre/m^2	-	ODA, 2011
Retail:				
Average UK supermarket	5	litres/m^2	-	Envirowise, 2002
Small store	3	litres/m^2	-	Envirowise, 2002
Schools and nurseries:				
Primary schools and nurseries	20	litres per pupil	-	DfES, 2002
Secondary schools	30	litres per pupil		DfES, 2002
Restaurants and bars:				
Typical medium-sized restaurant	54	litres/m^2	-	Dziegielewski et al., 2000.
Typical large bar and restaurant	147	litres/m^2	-	Dziegielewski et al., 2000.
Fast food outlet	90	litres/m^2	-	Dziegielewski et al., 2000.
Hospitals and medical centres:				
Hospitals	4.6	litres/m^2	-	DoH, 2013
Medical/health centre	2.5	litres/m^2	-	DoH, 2013
Hotels:				
Budget hotel	150	litres per bed-space	-	ODA, 2011
Luxury 4/5 star hotel	200	litres per bed-space	-	ODA, 2011
Olympic Sports Venues:				

Spectator	2	litres per spectator per hour		ODA, 2011
Staff	35	litres per staff per day		ODA, 2011
Competitors – all except for aquatic	35	litres per competitor per event		ODA, 2011
Competitors – aquatic	60	litres per competitor per event		ODA, 2011
Irrigation:				
Total amount of water required for irrigation during construction and Games phases (Ml)	74.55	ML		ODA, 2011
Total amount of water required for irrigation of green space during 1 year of legacy phase (Ml)	3.43	ML		ODA, 2011

Table A3. Materials and embedded carbon of the supermarket with gross internal floor area 7,530 m^2 (references: material quantities – SPON'S, 2013; embodied carbon – Hammond and Jones, 2008).

Supermarket	Quantity	Units	Density (kg/m3)	Weight (tonnes)	Embodied carbon (kg CO_2-eq/kg)	
					Virgin material	Recycled material
Reinforced concrete (RC30)	6960	m^2	2240	15,590	0.24	
Steel	336	tonne	7800	336	2.75	0.43
Concrete	7530	m^2	2400	18,072	0.13	
Aluminium	5995	m^2	2700	16,187	11.46	1.69
Polymeric roof insulation (PVC)	1640	m^2	1380	2,263	2.41	
Galvanized steel	890	m^2	7800	6,942	2.82	
Timber (flooring)	2160	m^2	650	1,404	0.46	
Ceramic tiles	540	m^2	1900	1,026	0.59	
Vinyl	425	m^2	1200	510	2.29	
Glass	25	m^2	2500	63	0.85	

Table A4. Materials and embedded carbon of the health centre for 60 consulting rooms with a gross internal floor area of 8,435 m^2 (references: material quantities – SPON'S, 2013; embodied carbon – Hammond and Jones, 2008).

Health centre	Quantity	Units	Density (kg/m3)	Weight (tonnes)	Embodied carbon (kg CO_2-eq/kg) Virgin material	Recycled material
Reinforced concrete (RC30)	12795	m^2	2240	28,661	0.24	
Polymeric roof covering (PVC)	1955	m^2	1380	2,698	2.41	
Aluminium	95	m^2	2700	257	2.75	0.43
Ceramic tiles	435	m^2	1900	827	0.59	
Concrete	10435	m^2	2400	25,044	0.13	
Clay tiles	1300	m^2	1900	2,470	0.46	
Plasterboard	13780	m^2	950	13,091	0.38	
Paint	20430	m^2	2100	42,903	3.56	
Vinyl	315	m^2	1200	378	2.29	
Linoleum	1100	m^2	1200	1,320	1.21	
Carpet (synthetic)	5500	m^2	160	880	3.9	
Glass	95	m^2	2500	238	0.85	

Table A5. Materials and embedded carbon of the small industrial unit with a gross internal area of 900 m^2 (references: material quantities – SPON'S, 2013; embodied carbon – Hammond and Jones, 2008).

Small industrial unit	Quantity	Units	Density (kg/m3)	Weight (tonnes)	Embodied carbon (kg CO_2-eq/kg) Virgin material	Recycled material
Reinforced concrete (RC30)	900	m^2	2240	2,016	0.24	
Steel frame (average steels)	36	tonne		36	2.75	0.43
Aluminium - general	1620	m^2	2700	4,374	11.46	1.69
Blockwork (concrete block 12 Mpa)	520	m^2	1850	962	0.08	
Steel doors (av. steel)	690	m^2	7800	5,382	2.75	0.43
Ceramic tiles	5	m^2	1900	10	0.59	
Plasterboard	15	m^2	950	14	0.38	
Paint (general)	36	tonne		36	3.56	
Emulsion paint (wet)	1370	m^2	2100	2,877	3.56	
Polycarbonate-foam	650	m^2	45	29	6	

Table A6. Materials and embedded carbon of the apartments block with a gross internal area floor area of 7,000 m^2 and net internal floor area of 5,590 m^2 (references: material quantities – SPON'S, 2013; embodied carbon – Hammond and Jones, 2008).

Apartments block	Quantity	Units	Density (kg/m3)	Weight (tonnes)	Embodied carbon ($kg CO_2$-eq/kg)	
					Virgin material	Recycled material
Reinforced concrete (RC30)	7666	m^2	2240	17,172	0.24	
Insulation (PVC foam)	1000	m^2	37	37	2.41	
Aluminium	10740	m^2	2700	28,998	11.46	1.69
Concrete	1605	m^2	2400	3,852	0.13	
Dense concrete block	4900	m^2	2240	10,976	0.098	
Plasterboard	17205	m^2	950	16,345	0.38	
Ceramic floor tiles	50	m^2	1700	85	0.59	
Carpet (heavy duty-rubber)	1050	m^2	400	420	6	
Ceramic tiles	3000	m^2	1900	5,700	0.59	
Timber	4530	m^2	650	2,945	0.46	
Carpet (synthetic)	4530	m^2	160	725	3.9	
Glass (double glazed windows)	4065	m^2	2500	10,163	0.85	

Table A7. Materials and embedded carbon of the typical UK three bedroom house with a total internal floor area of 91 m^2 and the total footprint of 46 m^2 (Monahan and Powell, 2011). (references: material quantities – Monahan and Powell, 2011; Iddon and Firth, 2013;embodied carbon for materials – Hammond and Jones, 2008; energy emissions coefficients – DEFRA, 2014).

Material and fuel	Quantity (kg)	Embodied carbon ($kg CO_2$-eq/kg)	
		Virgin material	Recycled material
Aluminium	260	11.46	1.69
Steel (average)	251	2.75	0.43
Brick	2,264	0.24	
Cement	2,023	0.83	
Concrete	56,651	0.18	
Gypsum plaster products	1,349	0.31	
Windows	1,277	1.56	
Doors (timber)	142	1.73	
HD polyethylene	56	1.7	
LD polyethylene	29	1.6	
Polythene	146	1.95	

Insulation	382	3.29	
Timber- composite board products	4,330	0.8	
Larch	1,315	1.08	
Engineered timber	222	0.68	
Softwood	6,792	0.45	
Main gas UK (kWh)	1,107	0.184	
Electricity (UK grid) (kWh)	11,106	0.45	
Diesel (l)	2,070	0.245	

Table A8. Materials and embedded carbon of the 13-stories London office with a gross internal area of 21,300 m^2 (references: material quantities – SPON'S, 2013; embodied carbon – Hammond and Jones, 2008).

London Office	Quantity	Units	Density (kg/m3)	Weight (tonnes)	Embodied carbon (kg CO_2-eq/kg)	
					Virgin material	Recycled material
Reinforced concrete (RC30)	6440	m^2	2240	14,426	0.24	
Lightweight reinforced concrete	17430	m^2	1600	27,888	0.21	
Structural steel (average)	2164	tonne		2,164	2.75	0.43
Paint	1350	tonne		1,350	3.56	
Profiled steel decking (av. steel)	1760	m^2	7800	13,728	2.75	0.43
Paving slabs (heavy cast)	1760	m^2	2400	4,224	0.16	
Aluminium	450	m^2	2700	1,215	11.46	1.69
Glass	400	m^2	2500	1,000	0.85	
Concrete	540	m^2	2400	1,296	0.13	
Blockwork (concrete block 12 Mpa)	3800	m^2	1850	7,030	0.08	
Stone cladding (white calcareous stone)	1870	m^2	2350	4,395	0.056	
Timber (flooring)	345	m^2	650	224	0.46	
Paint	7670	m^2	2100	16,107	3.56	
Plasterboard	4660	m^2	950	4,427	0.38	
Granite cladding	2050	m^2	2880	5,904	0.4	
Insulation (PVC foam)	1030	m^2	37	38	2.41	

Table A9. Materials and embedded carbon of the hotel with a gross internal floor area of 8,400m^2 (references: material quantities – SPON'S, 2013; embodied carbon – Hammond and Jones, 2008).

Hotel	Quantity	Units	Density (kg/m3)	Mass (tonnes)	Embodied carbon ($kg\ CO_2$-eq/kg)	
					Virgin material	Recycled material
Reinforced concrete (RC30)	2600	m^2	2240	5,824	0.24	
Precast concrete slab	10320	m^2	2400	24,768	0.18	
Insulation	1500	m^2	37	56	2.41	
Stainless steel	210	m^2	7800	1,638	6.15	
Glass	1170	m^2	2500	2,925	0.85	
Blockwork (concrete block 12 MPa)	1800	m^2	1850	3,330	0.08	
Aluminium	2500	m^2	2700	6,750	11.46	1.69
Hardwood	674	m^2	700	472	0.47	
Ceramic tiles	200	m^2	1700	340	0.59	
Timber	400	m^2	650	260	0.46	
Carpet (synthetic)	6400	m^2	160	1,024	3.9	
Cement	7500	m^2	1860	13,950	0.83	
Softwood	975	m^2	510	497	0.45	
Plasterboard	7300	m^2	950	6,935	0.38	

Table A10. Materials and embedded carbon of the 30-stories building with a total floor area of 26, 941 m^2 (references: material quantities – Yan et al., 2010; embodied carbon – Hammond and Jones, 2008; energy emission coefficients – DEFRA, 2014).

Material and fuel	Weight (tonnes)	Embodied carbon ($kg\ CO_2$-eq/kg)	
		Virgin material	Recycled material
Concrete (30 Mpa)	61,074	0.18	
Sand	19,671	0.005	
Steel bars	6,089	2.75	0.43
Glass and glazing	191	0.85	
Timber	96	0.46	
Aluminium	67	11.46	1.69
Stainless steel	34	6.15	
Granite	35	0.4	
Diesel (l)	246,001	0.245	
Electricity (kWh)	1,590,680	0.45 (kgCO2eq/kWh)	
Water (l)	16,804	0.34 (kgCO2eq/l)	

Table A11. Materials and embedded carbon of the community centre with a gross internal floor area of 860 m^2 with a very good BREAM rating (references: material quantities – SPON'S, 2013; embodied carbon – Hammond and Jones, 2008).

Community Centre	Quantity	Units	Density (kg/m3)	Mass (tonnes)	Embodied carbon ($kg\ CO_2$-eq/kg)	
					Virgin material	Recycled material
Reinforced concrete (RC30)	860	m^2	2240	1,926	0.24	
Steel	52	tonne	7800	52	2.75	0.43
Paint	52	tonne		52		
Plywood	887	m^2	540	479	0.81	
Polymeric roof insulation (PVC)	887	m^2	1380	1,224	2.41	
Aluminium	166	m^2	2700	448	11.46	1.69
Glass	25	m^2	2500	63	0.85	
Timber	312	m^2	650	203	0.46	
Plasterboard	1950	m^2	950	1,853	0.38	
Vinyl	300	m^2	1200	360	2.29	
Carpet (synthetic)	275	m^2	160	44	3.9	
Ceramic tiles	130	m^2	1700	221	0.59	
Laminate	250	m^2	700	175	0.51	

Table A12. Estimated amount and embodied carbon coefficients of materials used for construction of the Olympic Stadium (references: materials – London2012, 2007b; embodied carbon – Hammond and Jones, 2008).

Material	Weight (tonnes)	Embodied carbon ($kg\ CO_2$-eq/kg)
Concrete C40	202100	0.17
Reinforced concrete	17200	0.18
Precast concrete	5170	0.22
Reinforced cement (precast concrete)	308	0.22
Aggregate	224000	0.01
Blockwork, medium weight	13200	0.22
Steel	10000	2.75 (recycled 0.43)
Glass cladding	780	1.27
Roof cladding - polycarbonate fabric	162	6

Table A13. Estimated amount and embodied carbon coefficients of materials used for construction of the Media Centre (references: materials – London2012, 2007b; embodied carbon – Hammond and Jones, 2008).

Material	Weight (tonnes)	Embodied carbon ($kg\ CO_2$-eq/kg)
Aggregate	270	0.01
Asphalt	14	0.14
Bitumen	2	0.48
Sand	337	0.01
Stone	230	0.06
Timber	209	0.46
Carpet	155	3.9
Linoleum	10	1.21
Paint (wet)	394	3.56
Sealants and adhesives	29	3.85
Plastics	146	2.53
Vinyl flooring	8	2.29
Aluminium	756	11.46 (recycled 1.59)
Brass	70	2.42
Bronze	52	4.1
Copper	573	3.01
Iron	245	1.91
Lead	87	1.33
Steel (structural)	1,381	2.77
Steel	683	2.75 (recycled 0.43)
Tin	16	13.7
Windows	200	0.85
Zinc	56	3.31
Glass	135	0.85
Ceramics (tiles)	59	0.65
Bricks	562	0.22
Concrete	49,540	0.17
Plaster	2,386	0.38
Insulation	2,032	1.86
Paper	20	1.32
Rubber	20	3.18

Table A14. Estimated amount and embodied carbon coefficients of materials used for construction of the Olympic Village (references: materials – London2012, 2007b; embodied carbon – Hammond and Jones, 2008).

Material	Weight (tonnes)	Embodied carbon (kg CO_2-eq/kg)
Aggregate	8,804	0.01
Asphalt	267	0.14
Bitumen	22	0.48
Sand	12,783	0.01
Stone	1,838	0.06
Timber	1,873	0.46
Carpet	1,337	3.9
Linoleum	79	1.21
Paint (wet)	3,397	3.56
Sealants and adhesives	251	3.85
Plastics	1,297	2.53
Vinyl flooring	70	2.29
Aluminium	6,293	11.46 (recycled 1.59)
Brass	622	2.42
Bronze	474	4.1
Copper	5,081	3.01
Iron	2,193	1.91
Lead	773	1.33
Steel (structural)	4,624	2.77
Steel	6,074	2.75 (recycled 0.43)
Tin	135	13.7
Windows	1,532	0.85
Zinc	495	3.31
Glass	1,034	0.85
Ceramics	490	0.65
Bricks	4,527	0.22
Concrete	875,126	0.17
Plaster	21,384	0.38
Insulation	18,070	1.86
Paper	163	1.32
Rubber	170	3.18

Table A15. Estimated amount and embodied carbon coefficients of materials used for construction of the Aquatic Centre (references: materials – London2012, 2007b; embodied carbon – Hammond and Jones, 2008).

Material	Weight (tonnes)	Embodied carbon (kg CO_2-eq/kg)
0.75% reinforced concrete	10,622	0.18
1% reinforced concrete	9,758	0.18
1.5% reinforced concrete	3,147	0.19
2% reinforced concrete	44,774	0.2
2.5% reinforced concrete	3	0.21
3% reinforced concrete	1,371	0.22
Bitumen polymer	31	0.48
Concrete C40	14,514	0.17
Crushed concrete	17,160	0.17
Glass	13	0.85
HDPE	8	1.6
Soil	41,006	0.02
Polystyrene	79	2.7
Polystyrene, insulation	97	2.7
Reinforced concrete	29,964	0.19
Steel	2,938	2.75
Steel -rolled	1,880	2.77
Toughened glass	25	1.27
Temporary roof membrane	25	2.7
Temporary steel structure	1,975	2.75

Table A16. Estimated amount and embodied carbon coefficients of materials used for construction of the Olympic Park structure, highways and bridges (references: materials – London2012, 2007b; embodied carbon – Hammond and Jones, 2008).

Material	Weight (tonnes)	Embodied carbon (kg CO_2-eq/kg)
Steel	7,200	2.75
Concrete C40	170,638	0.17
Rebar - steel	8,500	2.77
Gabion stone	11,400	0.06
Fill	991,045	3.85
Kerbs and edgings - concrete	2,080	0.17
Drainage - concrete	1,660	0.17
Asphalt	389,045	0.14
Sand	695	0.01

Table A17. Estimated amount and embodied carbon coefficients of materials used for construction of the Olympic Park utilities (references: materials – London2012, 2007b; embodied carbon – Hammond and Jones, 2008).

Material	Weight (tonnes)	Embodied carbon (kg CO_2-eq/kg)
Clay pipe	425	0.49
Concrete	10,077	0.17
Concrete tiles	1,136	0.2
Copper	471	3.01
LDPE	18	1.7
Plastic pipe (PVC pipe)	1,346	2.5
Precast concrete	1,723	0.22
Rebar - steel	20	2.7
Reinforced concrete (2%)	758	0.2
Steel	732	2.7
Steel pipe	2,226	2.7
Fibreglass	22	8.1
Sand:cement (3:1)	15,175	0.21
Engineering bricks	732	0.63
Precast 0.5% reinforced concrete	60	0.22
Iron	29	1.91
Aggregate	1,296	0.01
Blockwork	33	0.22
Reinforced concrete (4%)	1,011	0.23
Precast concrete (3%)	11,449	0.26
Reinforced concrete (3%)	614	0.22
Stainless steel	13	6.15
Plastic	4	2.53
Aluminium	2	11.46 (recycled 1.59)
Reinforced fabric	101	2.7

Table A18. Estimated amount and embodied carbon coefficients of materials used for construction of the Olympic Park cabling, tunnelling and fencing (references: materials – London2012, 2007b; embodied carbon – Hammond and Jones, 2008).

Material	Weight (tonnes)	Embodied carbon (kg CO_2-eq/kg)
Plastic	3,630	2.53
Copper	3,370	3.01
Fibre-reinforced concrete	43,200	0.45
Steel	24	2.75
Lubricant	643	0.62
Brackets	5	2.75
Plywood	231	0.81

Table A19. Estimated amount and embodied carbon coefficients of materials used for construction of the Olympic Park Energy Centre (references: materials – London2012, 2007b; embodied carbon – Hammond and Jones, 2008).

Material	Weight (tonnes)	Embodied carbon (kg CO_2-eq/kg)
Stone	11	0.06
Timber	57	0.46
Windows	8	0.85
Carpet	10	3.9
Linoleum	1	1.21
Paint	54	3.56
Sealants and adhesives	3	3.85
Plastics	19	2.53
Vinyl flooring	1	2.29
Aluminium	66	11.46 (recycled 1.59)
Brass	10	2.42
Bronze	6	4.1
Copper	88	3.01
Iron	35	1.91
Lead	11	1.33
Steel (structural)	83	2.75
Steel	103	2.7
Tin	2	13.7
Zinc	9	3.31
Glass (toughened)	2	1.27
Ceramics	8	0.65
Bricks (clay)	183	0.46
Concrete C40	2,991	0.17
Plaster	203	0.38
Insulation (general)	287	1.86
Paper	2	1.32
Rubber	2	3.18

Table A20. Emissions conversion factors for water, electricity, fuels and transport.

Fuel	Unit	Emissions conversion factor	Reference
UK electricity	kg CO_2-eq/kWh	0.45	DEFRA, 2014
UK water supply	kg CO_2-eq/l	0.34	DEFRA, 2014
UK water treatment	kg CO_2-eq/l	0.709	DEFRA, 2014
Natural gas	kg CO_2-eq/kWh	0.18	DEFRA, 2014
Petrol (average biofuel blend)	kg CO_2-eq/l	2.21	DEFRA, 2014
Diesel (average biofuel blend)	kg CO_2-eq/l	2.601	DEFRA, 2014
Passenger car - petrol (average)	kg CO_2-eq/km	0.198	DEFRA, 2014
Passenger car - diesel (average)	kg CO_2-eq/km	0.183	DEFRA, 2014
London bus	kg CO_2-eq/passenger.km	0.103	DEFRA, 2012
Rail	kg CO_2-eq/passenger.km	0.076	DEFRA, 2012
Coach	kg CO_2-eq/passenger.km	0.036	DEFRA, 2012
Eurostar	kg CO_2-eq/passenger.km	0.017	DEFRA, 2012
Ferry	kg CO_2-eq/passenger.km	0.16	DEFRA, 2012
Longhaul flight-economy	kg CO_2-eq/passenger.km	0.17	DEFRA, 2014
Longhaul flight-first	kg CO_2-eq/passenger.km	0.67	DEFRA, 2014
Shorthaul flight-economy	kg CO_2-eq/passenger.km	0.18	DEFRA, 2014
Shorthaul flight-business	kg CO_2-eq/passenger.km	0.28	DEFRA, 2014
Domestic flight	kg CO_2-eq/passenger.km	0.33	DEFRA, 2014
Freight transport - rail	kg CO_2-eq/tonne.km	0.063	DEFRA, 2014
Freight transport - barge	kg CO_2-eq/tonne.km	0.1	DEFRA, 2014
Freight transport - road	kg CO_2-eq/tonne.km	0.112	DEFRA, 2014

Table A21. Maximum transport distances for reclaimed materials (WRAP, 2008; Hammond and Jones, 2008).

Material	Distance (km)	Embodied carbon (kg CO_2-eq/kg)
Reclaimed tile	100	0.22
Reclaimed stone	300	0.06
Reclaimed bricks	250	0.04
Reclaimed timber	1,000	0.06
Reclaimed steel	2,500	0.43
Reclaimed aluminium	2,500	1.69

Table A22. Assumed transportation distance of materials (London2012, 2007b).

Material	Distance (km)
Aggregate	76
Asphalt	64
Bitumen	64
Sand	16
Stone	198
Timber	139
Carpet	139
Linoleum	64
Paint	64
Sealants and adhesives	64
Plastics	64
Vinyl flooring	64
Aluminium	115
Brass	115
Bronze	115
Copper	115
Iron	115
Lead	115
Steel	115
Tin	115
Windows	115
Zinc	115
Glass	64
Ceramics	64
Bricks/blockwork	64
Concrete	98
Plaster	64
Insulation	64
Paper	64
Rubber	64
Other	64

Table A23. Estimated quantities of waste generated in each type of building.

Type of building	Quantity of waste	Unit	Reference
Residential dwelling	457	kg/resident/year	DEFRA, 2011
Commercial office	200	kg/employee/year	UoE, 2011
Medical centres (non-clinical waste only)	2.5	kg/patient/year	SRH, 2013
Primary school/nursery	45	kg/pupil/year	Biffa, 2012
Secondary school	38	kg/pupil/year	Biffa, 2012
Small restaurant	38	t/year	WRAP, 2011
Medium restaurant	67	t/year	WRAP, 2011
Large restaurant	97	t/year	WRAP, 2011
Hotel (medium size 150 employees)	152	t/year	WRAP, 2011
Hotel (large 250+ employees)	339	t/year	WRAP, 2011
Supermarket (average size)	3000	t/year	NN, 2012
Sports venues	0.14	kg/spectator/event	RW, 2013

Table A24. Estimated daily number of competitors, staff and spectators in the Olympic Park sports venues during the Games period (ODA, 2011).

Venue	**Number of spectators**	**Number of competitors**	**Number of stuff**
Broadcast Centre			54,120
Aquatic Centre	17,500	6,388	1,460
Olympic Stadium	80,000	426	9,316
Etonmanor	3,520	4,310	498
Handball Arena	5,520	228	546
Velodrome	3,120	224	256
Hockey Centre	10,610	140	1,241
Basketball Arena	10,620	173	1,815
Fencing Arena	4,320	86	637
Waterpolo	2,100	42	345
Sponsors' Village			14,182
Security			5,400
Catering	200,000		

Table A25. Estimated annual number of spectators, visitors and employees in the sports venues operating on site in the legacy phase (assuming only 5 permanent venues are in operation) (ODA, 2011).

Venue	Number of spectators	Number of competitors	Number of stuff
Olympic Stadium	310,000	8,000	6,300
Aquatic Centre	50,000	700,000	14,725
Hockey Centre	98,550	152,231	17,350
Handball Arena	130,000	202,875	15,025
Velodrome	547,570	179,180	50,735

Table A26. Average distance travelled by each type of visitor/official (London2012, 2007b).

Visitor's/official's category	Average distance travelled – return trip (km)
Visitors origin:	
London	24
UK	330
Europe	2,600
Rest of the World (RoW)	15,000
Travel Grant	15,000
Official's type:	
Athletes and families	5,000
Media	5,000
Officials	7,140
Employees and volunteers	40

Appendix 2. Assumptions for the post-event site design scenarios.

Scenario 1 – 'Business as Usual'

- Total number of new residential dwellings is 6,800 (4,000 apartments and 2,800 houses). One 10-storey apartment block with the total gross internal floor area of 7,000 m^2 consists of 100 units (SPONS's, 2013). One typical UK three bedroom house has a gross internal floor area of 91 m^2 and a total footprint of 46 m^2 (Monahan and Powell, 2011). In this scenario assume 40 10-storey apartment blocks with 10 apartments on each floor. The total footprint area of all residential buildings is 408,000 m^2. The following constraints were introduced for the baseline scenarios:
    - Detached houses – minimum 5% of the total number of the residential dwellings;
    - Semi-detached houses – minimum 5% of the total number of the residential dwellings;
    - Terraced houses – minimum 30% of the total number of the residential dwellings;
    - Bungalows – minimum 2% of the total number of the residential dwellings;
    - 2 bedroom flats – minimum 20% of the total number of the residential dwellings;
    - 1 bedroom flats – minimum 20% of the total number of the residential dwellings.
- Two typical 13-storey London offices with the gross internal floor area of 21,300 m^2, net internal floor area of 14,600 m^2 and a total footprint of 1,638 m^2 and 4 small industrial units with the gross internal floor area and a total footprint of 900 m^2 (SPON's, 2013). Total footprint of all commercial buildings is 46,200 m^2. The following constraints were introduced for the baseline scenarios:
    - Office type 1 (no canteen, naturally ventilated cellular) – minimum 3% of the total area of all commercial offices;

    - Office type 2 (no canteen, naturally ventilated open plan) – minimum 0.3% of the total area of all commercial offices;
    - Office type 3 (with canteen, air conditioned standard) – minimum 95% of the total area of all commercial offices.
- Two community centres with the gross internal floor area and the total footprint of 860 m^2 (SPON's, 2013).
- 40 fast food restaurants (total floor area of 1 fast food restaurant is 100 m^2) and 40 medium size restaurants (total floor area of 1 medium size restaurant is 743 m^2), with the total floor area of 33,720 m^2.
- One 10-storey hotel with the total floor area of 16,800 m^2, net internal floor area of 6,720 m^2 and a total footprint of 1,680 m^2.
- Total retail area is assumed to be equal to the size of 3 average supermarkets each with the gross internal floor area of 7,530 m^2. Total floor area is 22,590 m^2.

Scenario 2 – 'Commercial World'

- Ten 10-storey apartment block with 10 apartments on each floor with the total floor area of all apartment blocks being 70,000 m^2. The following constraints were introduced for the baseline scenarios:
    - 2 bedroom flats – minimum 40% of the total number of the residential dwellings;
    - 1 bedroom flats – minimum 10% of the total number of the residential dwellings.
- 15 typical 13-storey London offices each with the floor area of 21,300 m^2 and 30 industrial units each with the floor area of 900 m^2. Total internal floor area of all commercial buildings is 4,180,500 m^2. The following constraints were introduced for the baseline scenarios:
    - Office type 1 (no canteen, naturally ventilated cellular) – minimum 1% of the total area of all commercial offices;
    - Office type 2 (no canteen, naturally ventilated open plan) – minimum 40% of the total area of all commercial offices;
    - Office type 3 (with canteen, air conditioned standard) – minimum 25% of the total area of all commercial offices;

  - Office type 4 (with canteen, air conditioned prestige) – minimum 25% of the total area of all commercial offices.
- 50 fast food outlets and 20 medium size restaurants with a total floor area of 19,860 m^2. Assume 50% of the restaurant buildings are 1-storey and 50% are two-storey buildings.
- Total retail area is assumed to be equal to the size of 5 average supermarkets with the total internal floor area of 37,650 m^2. Assume that the total footprint area is 70% of the total internal floor area.
- 5 hotels with the total internal floor area of 84,000 m^2.
- 1 community centre with the total floor area of 860 m^2.

Scenario 3 – 'High rise, high density'

- 40 high rise residential buildings (50% of the residential buildings are 20-storey buildings and 50% are 30-storey). Each floor has a total area of 898 m^2, thus the total floor area of all residential buildings is 898,000 m^2. Assume that there are 8 apartments on each floor of the residential building. Therefore, the total number of apartments is assumed to be 16,000. The following constraints were introduced for the baseline scenarios:
  - 3 bedroom flats – minimum 30% of the total number of the residential dwellings;
  - 2 bedroom flats – minimum 20% of the total number of the residential dwellings;
  - 1 bedroom flats – minimum 20% of the total number of the residential dwellings.
- 30 high rise office buildings (50% of the office buildings are 25-storey, 50% are 30-storey buildings). Each floor has a total area of 2,563 m^2 (Yan et., 2010). Total internal floor area of all office buildings is 2,114,475 m^2. The following constraints were introduced for the baseline scenarios:
  - Office type 1 (no canteen, naturally ventilated cellular) – minimum 1% of the total area of all commercial offices;

  - Office type 3 (with canteen, air conditioned standard) – minimum 4 % of the total area of all commercial offices;
  - Office type 4 (with canteen, air conditioned prestige) – minimum 90% of the total area of all commercial offices.
- Total area of retail space is equal to the size of 15 supermarkets each with the floor area of 7,530 m^2. Total floor area is 112,950 m^2. Assume that 1/3 of the total area is comprised of 2-storey buildings, the rest are 1-storey buildings.
- 7 community centres with the total floor area of 6,020 m^2.
- 10 small industrial units with the total area of 9,000 m^2.
- 5 20-storey hotels with the total floor area of 168,000 m^2.
- 10 large restaurants (each with a floor area of 1,858 m^2), 30 medium size restaurants (each with a floor area of 743 m^2) and 100 fast food outlets (each with a floor area of 100 m^2). Total floor area of all restaurants is 50,870 m^2.

Appendix 3. Optimisation results.

Table A27. Shares of each type of the residential building for the baseline and optimum scenarios.

Share of each residential building type (percentage of the total number of residential buildings)	**BAU**		**CW**		**HRHD**	
	Baseline	**Optimum**	**Baseline**	**Optimum**	**Baseline**	**Optimum**
R1 - detached house	5%					
R2 - semi-detached house	5%					
R3 – terraced house	30%					
R4 – bungalow	2%		40%			
R5 – 3-bedroom flat	0				30%	
R6 – 2-bedroom flat	20%				20%	
R7 – 1 bedroom flat	38%	100%	60%	100%	50%	100%

Table A28. Amount of each type of the office building for the baseline and optimum scenarios.

Amount of each type of office buildings (m^2)	BAU		CW		HRHD	
	Baseline	**Optimum**	**Baseline**	**Optimum**	**Baseline**	**Optimum**
O1 - no canteen, naturally ventilated cellular	3,900	237,965	27,000	4,487,578	9,000	2,590,616
O2 - no canteen, naturally ventilated open plan			2,065,000			
O3 - with canteen, air conditioned standard	133,962		1,133,962		91,000	
O4 – with canteen, air conditioned prestige			1,045,538		2,114,475	
RE1 – large restaurant					18,580	
RE2 – medium restaurant	29,720		14,800		14,860	
RE3 – fast-food restaurant	4,000		5,000		10,000	
SC – schools and nurseries	22,546		7,2822		40,796	
MC – medical centres	2,727		946		4,935	
LH- luxury hotel			67,200		168,000	
BH – budget hotel	16,800		16,800			
RS – retail/supermarket	22,590		37,650		112,950	
CC- community center	1,720		860		6,020	

Table A29. Transport modes for the optimum scenarios (minimum constraints were set to 1% for all transport modes; no maximum constraints except for 'cycle' mode –max 10%).

Transport mode	London	UK	Europe	Rest of the World	Athletes	Media	Officials	Emplo yees	Travel Grant
Car petrol/diesel	1%	1%	1%						
Long-haul flight-economy				99%	1%	1%	97%		99%
Long-haul flight-first class							1%		
Short-haul flight-economy			1%	1%	1%	1%	1%		1%
Short-haul flight-business			1%				1%		
UK domestic		1%							
London bus	1%							1%	
Rail	1%	1%			98%	98%		89%	
Coach	87%	97%	1%						
Eurostar			95%						
Cycle	10%							10%	
Ferry			1%%						

Appendix 4. Modelling Integrated Waste Management Systems (IWMSs) using GaBi Product Sustainability Software for LCA.

Figure A1 provides a hierarchical scheme of the IWMS 4 model. All processes are presented in Level 1: Anaerobic digestion, MRF, Energy-from-Waste incineration plant. Each process is modelled individually in level 2. Additional processes associated with each process from level 2 are shown in level 3.

Figures A2 – A6 provide screenshots of the models developed using GaBi 6.0 Product Sustainability Software. Figure A7 provides an example of how each process is modelled and what is contained within ‘the box’ regarding the anaerobic digestion process (highlighted in green in Figure A3).

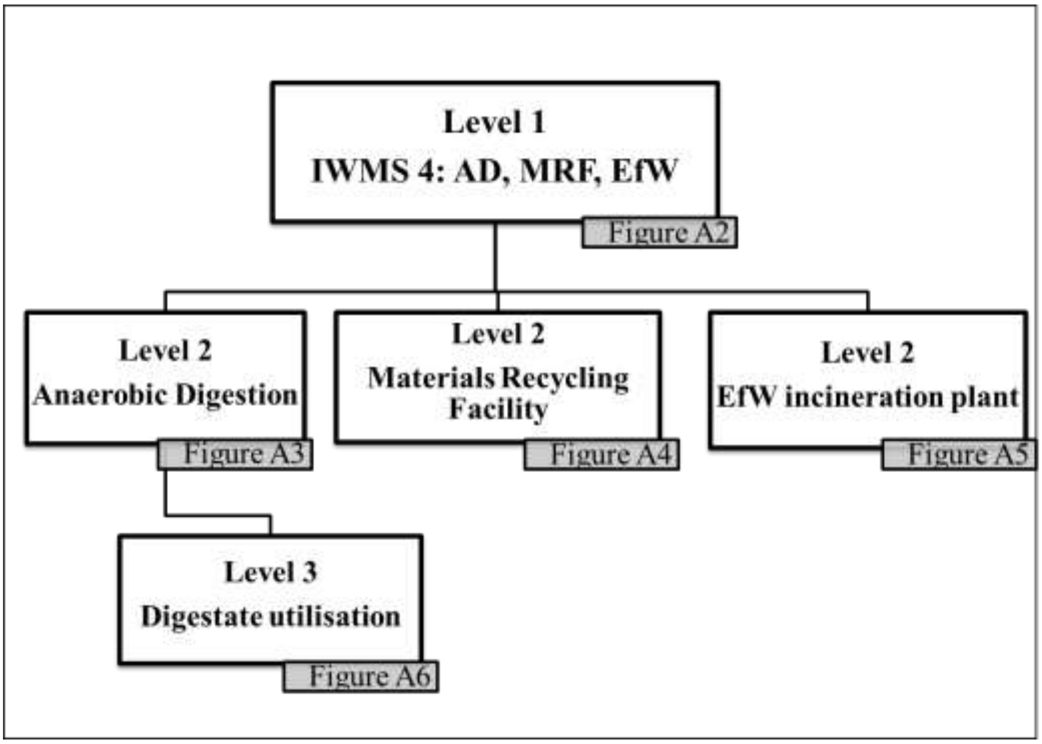

Figure A 1. Overall hierarchy of the waste treatment processes for the IWMS 4 modelled in GaBi 6.0 Product Sustainability Software.

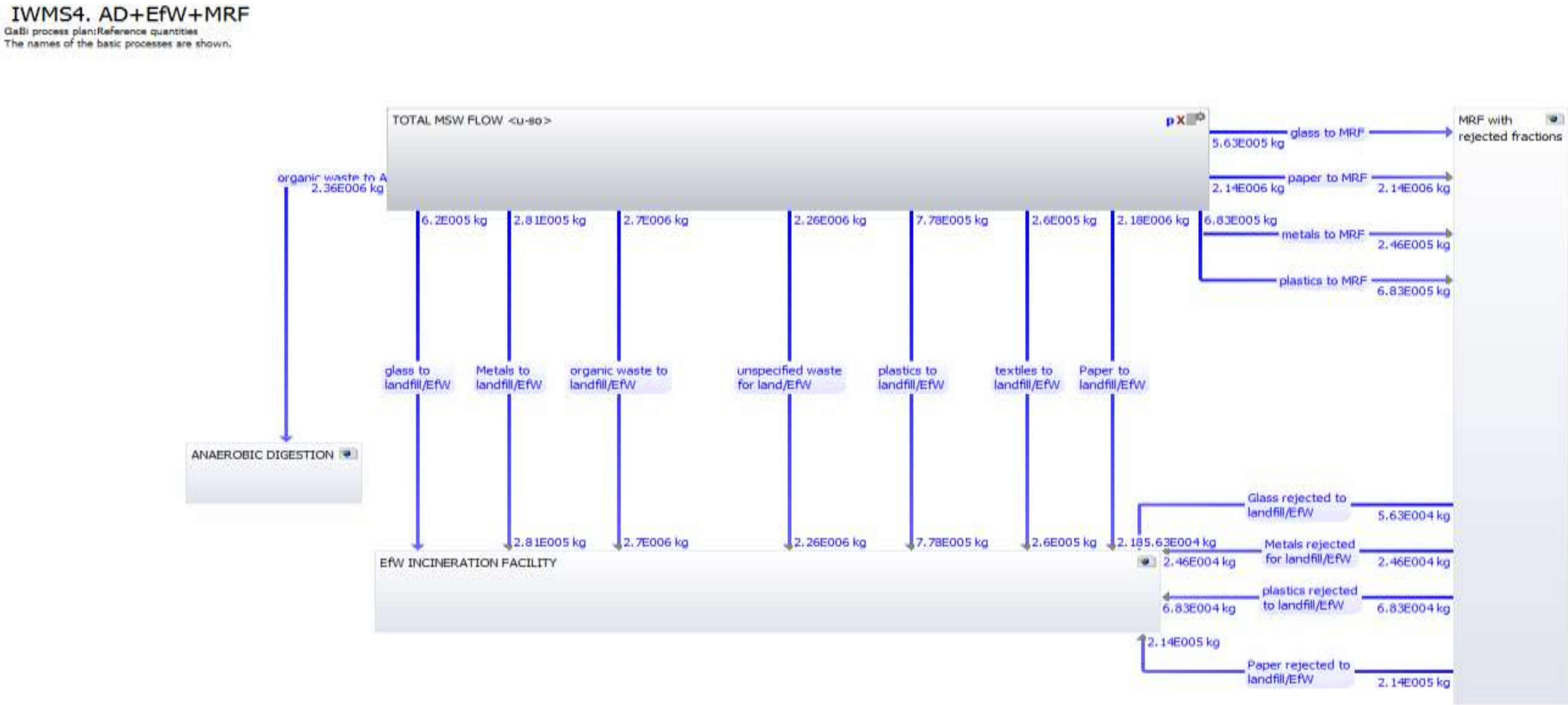

Figure A 2. IWMS 4. Level 1: Anaerobic Digestion process, Incineration process (EfW), Recycling process (MRF).

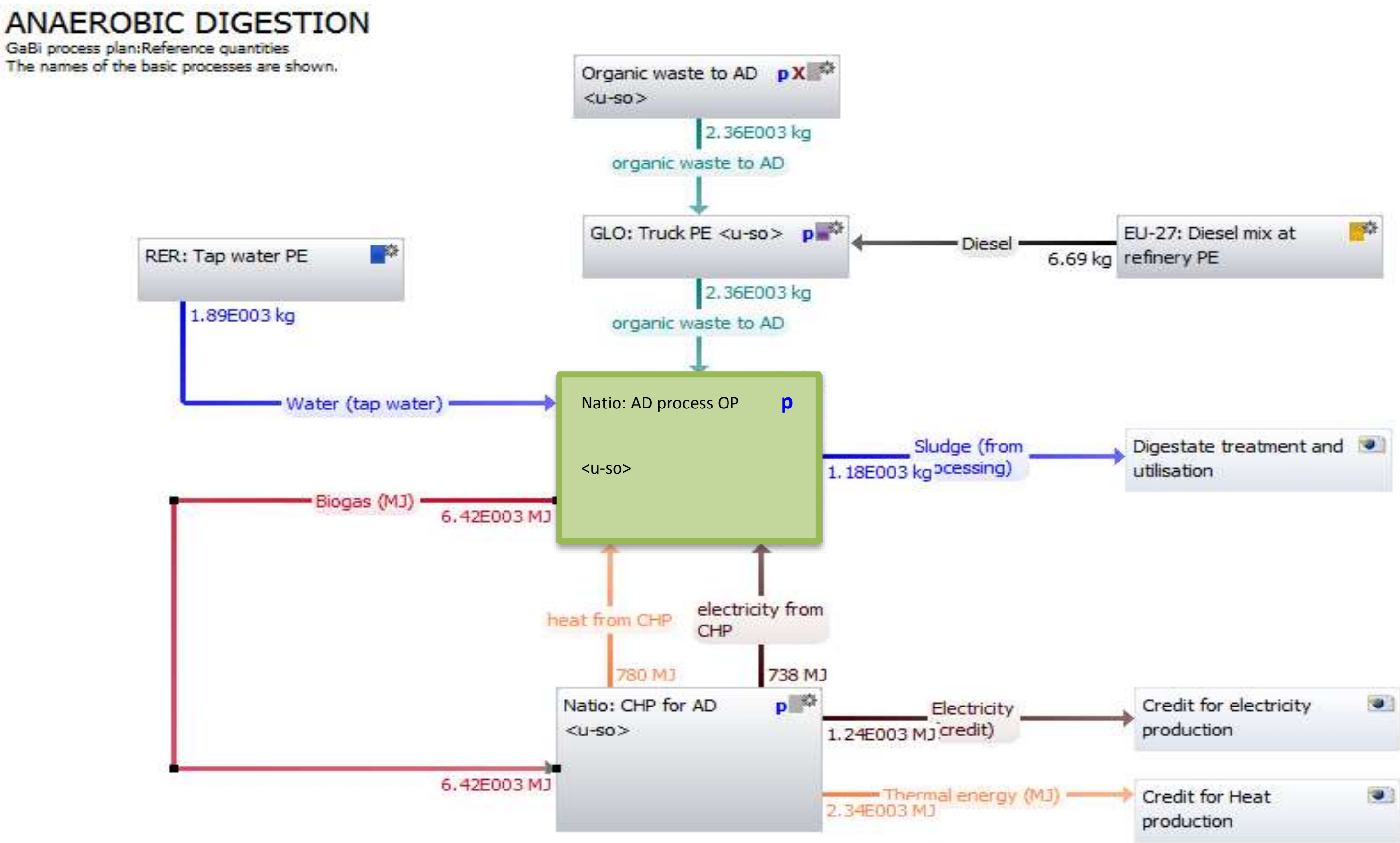

Figure A 3. Level 2: Anaerobic digestion process (includes biogas production and credits for energy generation from biogas).

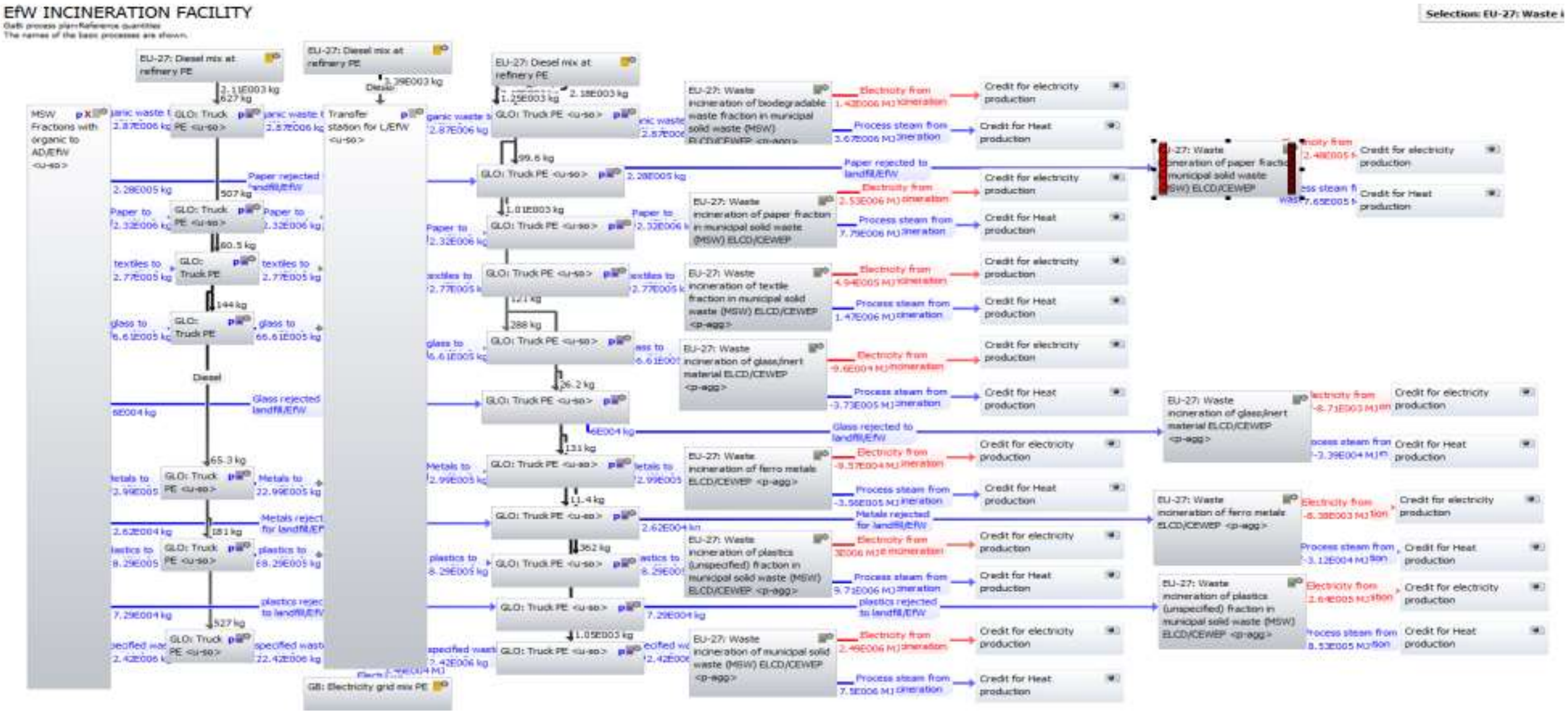

Figure A 4. Level 2: Incineration in EfW plant (includes transportation of MSW to/from transfer station and credits for electricity and heat generated from MSW).

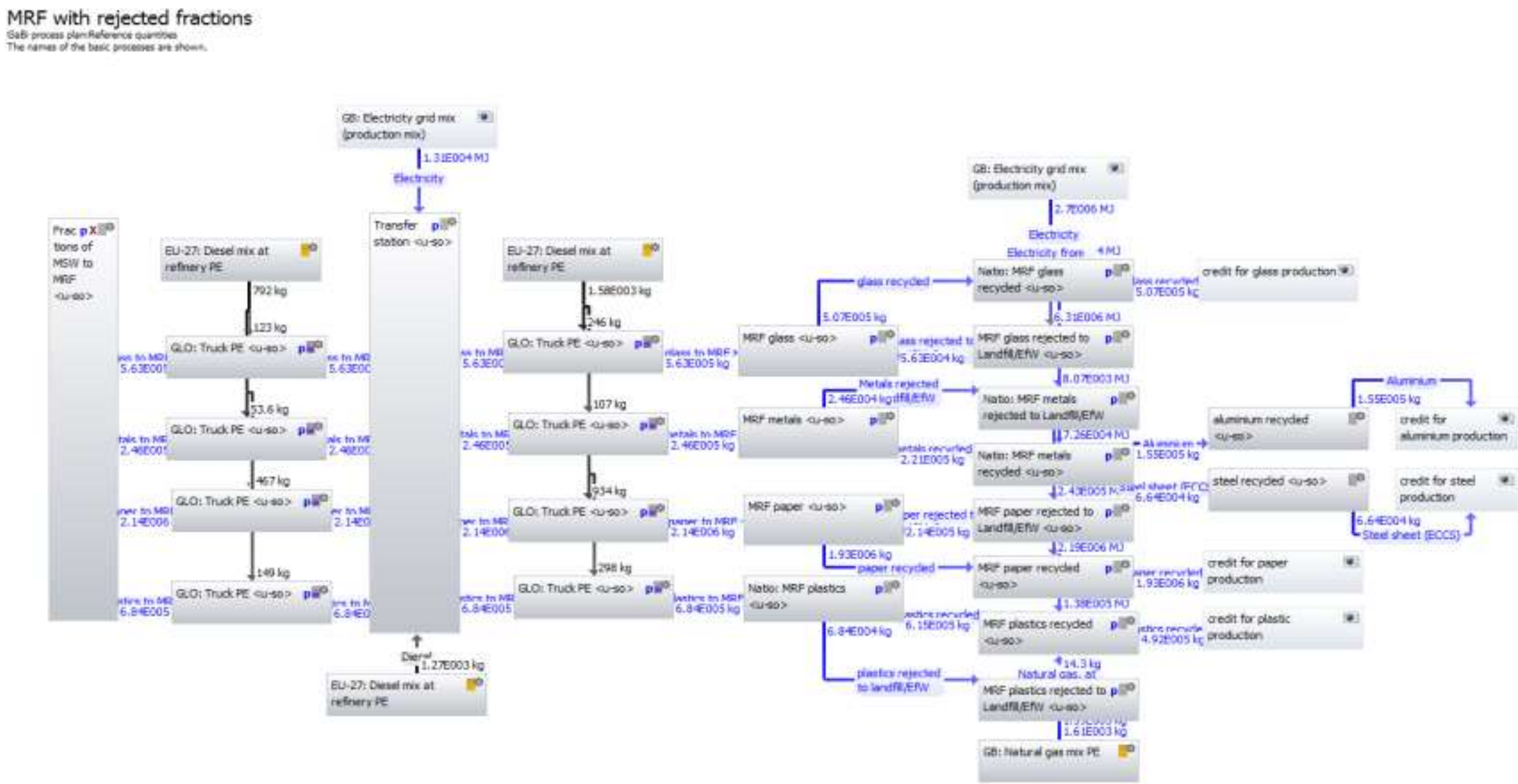

Figure A 5. Level 2: Recycling at the MRF (includes transportation of source-separated MSW streams to/from transfer station and credits for materials recovery).

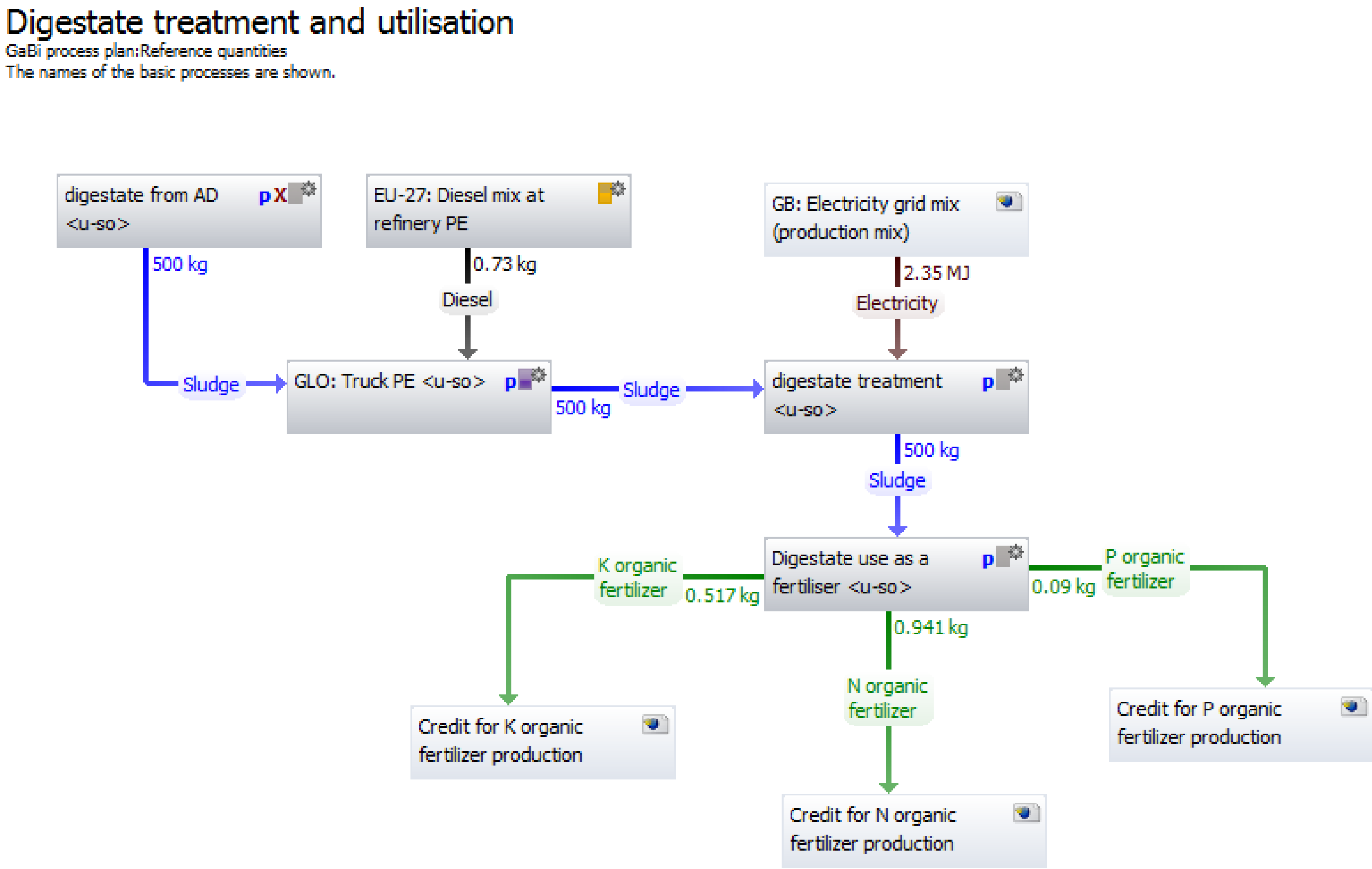

Figure A 6. Level 3: Digestate utilisation (includes transport and spreading of digestate on arable land and credits for nutrients recovery).

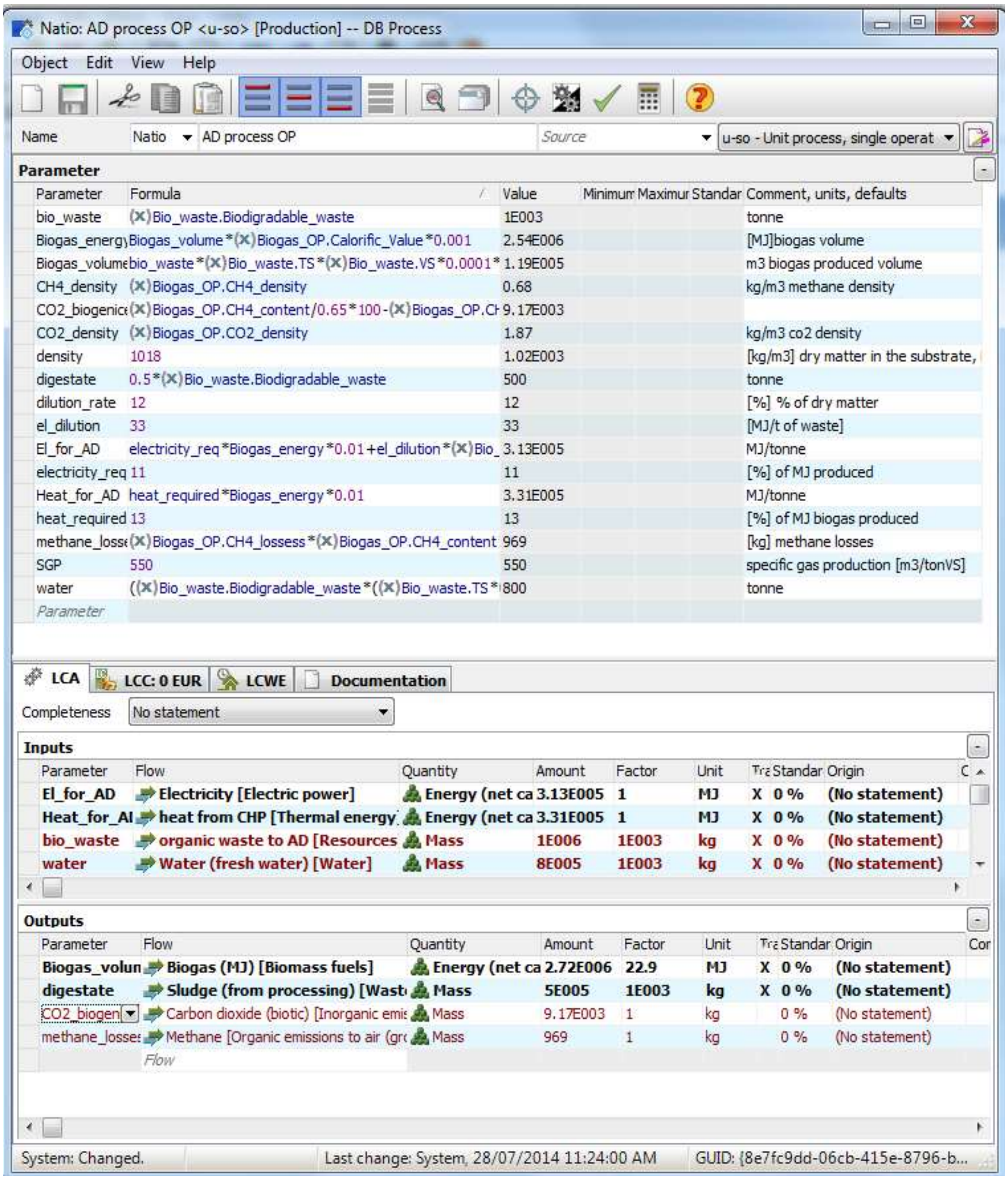

Figure A 7. Anaerobic digestion process modelling. The figure illustrates what is 'inside the box' of the AD process (highlighted in green in Figure A3).

Appendix 5. Publications and presentations.

Parkes, O., Bogle, I.D.L., Lettieri, P., 2011. *Towards defining a quantitative methodology to enhance the sustainability performance of major international events*. Presented at the Annual Centre for Process System Engineering (CPSE) Industrial Consortium Meeting, Imperial College London, London, UK, December 2011.

Parkes, O., Bogle, I.D.L., Lettieri, P., 2012. *Towards defining a quantitative methodology to enhance the sustainability performance of major international events.* Presented at the 22nd European Symposium on Computer Aided Process Engineering, University College London, London, UK, June 2012.

Parkes, O., Bogle, I.D.L., Lettieri, P., 2012. *Towards defining a quantitative methodology to enhance the sustainability performance of major international events.* Computer Aided Chemical Engineering, 30, 46-50.

Parkes, O., Lettieri, P., 2012, Bogle, I.D.L. *Sustainability assessment of mega-events from a life cycle assessment perspective. A case study – the London Olympic Park*. In Proceedings of the 1st International Conference on Urban Sustainability and Resilience, London, UK, November 2012.

Parkes, O., Lettieri, P., Bogle, I.D.L., 2013. *Sustainability of mega-events. Application of life cycle assessment to waste management systems*. Presented at the ChemEng Day, Imperial College London, London, UK, March 2013.

Parkes, O., Lettieri, P., Bogle, I.D.L., 2013. *Defining a quantitative methodology for sustainability assessment of mega-events*. Presented at the 7th International Conference of the International Society for Industrial Ecology. University of Ulsan, Ulsan, Korea, June, 2013.

Parkes, O., Lettieri, P., Bogle, I.D.L., 2013. *Defining a quantitative methodology for sustainability assessment of mega-event projects.* Presented at the Annual Centre for Process System Engineering (CPSE) Industrial Consortium Meeting, Imperial College London, London, UK, December 2013.

Parkes, O., Lettieri, P., Bogle, I.D.L., 2014. *Life Cycle Assessment of integrated waste management systems for alternative legacy scenarios of the London Olympic Park*. Waste Management – under review.