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Research article

Defining a quantitative framework for evaluation and optimisation of the environmental impacts of mega-event projects

Olga Parkes [a], Paola Lettieri [a], I.David L. Bogle [b,*]

[a] Department of Chemical Engineering, University College London, Torrington Place, London WC1E 7JE, UK
[b] Centre for Process Systems Engineering, University College London, Torrington Place, London WC1E 7JE, UK

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ABSTRACT

This paper presents a novel quantitative methodology for the evaluation and optimisation of the environmental impacts of the whole life cycle of a mega-event project: construction and staging the event and post-event site redevelopment and operation. Within the proposed framework, a mathematical model has been developed that takes into account greenhouse gas (GHG) emissions resulting from use of transportation fuel, energy, water and construction materials used at all stages of the mega-event project.

The model is applied to a case study - the London Olympic Park. Three potential post-event site design scenarios of the Park have been developed: Business as Usual (BAU), Commercial World (CW) and High Rise High Density (HRHD). A quantitative summary of results demonstrates that the highest GHG emissions associated with the actual event are almost negligible compared to those associated with the legacy phase. The highest share of emissions in the legacy phase is attributed to embodied emissions from construction materials (almost 50% for the BAU and HRHD scenarios) and emissions resulting from the transportation of residents, visitors and employees to/from the site (almost 60% for the CW scenario). The BAU scenario is the one with the lowest GHG emissions compared to the other scenarios. The results also demonstrate how post-event site design scenarios can be optimised to minimise the GHG emissions. The overall outcomes illustrate how the proposed framework can be used to support decision making process for mega-event projects planning.

1. Introduction

Mega-events can be defined as the large-scale cultural, commercial or sport events that involve substantial capital investment and different stakeholder groups, enhance urban regeneration, political and economic status of the host city and attract global media attention (Roche, 2000; Getz, 2008; Lee et al., 2014). The most well-known mega-events are the Olympic Games, FIFA World Cup and a World Fair such as the Expo events. Mega-events normally result in numerous economic and social benefits for the host city such as the increased number of tourists, major investment in infrastructure projects, creation of new jobs, sport education, etc. Mega-events are also associated with various environmental impacts due to the vast amounts of construction materials, energy and resource use, waste generation, air and noise pollution during the construction of the event site, staging the event and post-event site redevelopment and operation. Therefore, a mega-event as an overall project can be described as a long-term multi-billion dollar project comprised of multiple phases of different duration which involves complex planning process and a vast array of different stakeholders.

Environmental strategies for the mega-events have recently become a fundamental part of the overall events' sustainability management plans. Typically, they specify the actions that are going to be implemented in order to minimise negative environmental impacts resulting from the preparation and staging of the event. In the last few decades, the range of such actions has expanded significantly from merely planting new trees to complex energy recycling schemes and innovative sustainable venue designs and materials. Nowadays, the event organisers also publish the post-event reports where they specify the progress against the initial targets such as the London 2012 Post-Games Sustainability Report 'A legacy of change' (LOCOG, 2012).

* Corresponding author.
E-mail addresses: o.parkes@ucl.ac.uk (O. Parkes), d.bogle@ucl.ac.uk (I.DavidL. Bogle).

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A number of sustainability and environmental guidelines and standards have recently been developed which assist event organisers with implementation of sustainability measures during the preparation and staging of the event. Some guidelines are universal for all types of organisations such as ISO 14001-14006 'Environmental Management Systems' (ISO, 2014a) or ISO26000 'Social Responsibility' (ISO, 2014b). Others, such as BS8901′ Specification for a Sustainability Management System for Events' (BSI, 2014) or ISO 20121 'Event Sustainability Management Systems' (ISO, 2012) were developed specifically for the events management. Although the standards provide some useful recommendations for the event organisers, they do not specify any quantitative targets or define a set of indicators or tools that should be used to measure the performance progress. Moreover, they generally address the preparation or the event phase without considering the post-event legacy phase.

From the host city's perspective, the legacy is by far the most important phase of a mega-event project. The actual event only lasts a few weeks and the duration of the legacy phase is decades. Since the 1990s, the significance of securing a positive lasting legacy created by a mega-event has been widely recognised (IOC, 2007). It is now emphasised 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). Therefore, sustainable planning of mega-event projects should shift from focusing on the construction and event stages only to a holistic assessment of the whole project's life cycle including the post-event legacy phase. This is because the major use of the infrastructure built for the event from a host city's perspective is the legacy phase. The legacy is by far the longest phase of a mega-event project and this is where most of the environmental impacts will occur (GIZ AgenZ, 2013).

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 focus on the evaluation of economic impacts and utilisation of the built infrastructure in the post-event period (e.g., Hiller, 2006; Li et al., 2013). A number of conceptual frameworks for measuring legacies of mega-events have been recently proposed. Most of them, however, focus on the evaluation of potential tourism legacy such as the theoretical framework proposed by Li and McCabe (2013). Therefore, a critical review of the latest studies on sustainability assessment of mega-event projects reveals that a quantitative environmental assessment of mega-events mainly includes the impacts associated with the actual event or the construction of the event venues. Hence, there is no a common standard or a uniform methodology that could be applied for a holistic quantitative assessment and comparison of the environmental impacts of mega-event projects, as also observed by other authors (e.g. Collins et al., 2009).

This paper presents a novel quantitative framework that can be used during the planning process for mega-event projects in order to assist decision makers with the evaluation and optimisation of the environmental impacts of the proposed site design scenarios. The framework and a case study are described in Section 2. Section 3 provides a mathematical formulation of the optimisation model developed within the proposed framework. Section 4 presents the outcomes and analysis of the computational results. The final section outlines the overall conclusions and future work.

2. Methodology and a case study

2.1. Mega-event project as a complex system

As defined earlier, a mega-event project is a long-term large-scale project with multiple sub-projects of different scope and duration. Fig. 1 provides a holistic representation of a mega-event as a complex system with numerous inputs such as materials, labour and energy, and outputs, such as infrastructure, employment and services (Parkes et al., 2012). The activities within the system also cause environmental impacts, which may be both positive and negative.

The overall system is divided into three main subsystems according to the phases of the project: construction, event and legacy. Each subsystem consists of other sub-subsystems and all of them 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 stage because this is where the most significant aspects and various alternatives of the proposed site design scenarios are being developed and evaluated. Thus, concurrent planning of the construction of the event site and post-event site redevelopment and evaluation of the environmental impacts of the alternative design scenarios is fundamental to ensure that the project continues delivering sustainable positive impacts long after the event is over. Section 2.2 presents a novel framework for the holistic environmental assessment of mega-event projects that can be used to evaluate and optimise the emissions resulting from each stage of the project.

2.2. Summary of the proposed quantitative framework

The quantitative framework presented in this paper requires a set of proposed scenarios for the event and its legacy. It provides quantitative evidence for decisions to be made about future development by comparing optimised conditions for each scenario. It takes into account the environmental impacts of the following aspects: water supply and wastewater removal during the construction and operation of the event and post-event venues; fuel used for transportation of construction materials and demolition waste during the construction of the event site and redevelopment of the post-event site, and fuel used for transportation of visitors during the event and legacy phases; embodied emissions from construction materials; energy used during construction of event venues and infrastructure and operation of the event during the event and post-event phases (see Table 1). In this work, the environmental impacts associated with greenhouse gas (GHG) emissions are accounted for, which is mandatory for the UK companies' environmental reporting (DEFRA, 2013). The three main greenhouse gases are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The results are expressed in kg of carbon dioxide-equivalent (kg CO_2-eq).

Environmental impacts resulting from management of municipal solid waste (MSW) is not considered in this study because of the complexities of various integrated waste management systems. The authors propose different evaluation framework for the environmental assessment of MSW management options using life cycle assessment (LCA) which is described in detail in Parkes et al. (2015).

Within the proposed framework, a mathematical model has been developed that takes into account the GHG emissions summarised in Table 1. The objective of the model is to minimise the environmental impacts of different stages of a mega-event project for each proposed scenario, subject to a number of constraints described in Section 3.

The model can be used at different stages of the project. First, it can be used at the design phase to evaluate and optimise the environmental impacts of the construction of alternative event site design scenarios. The results obtained for the specific event can also serve as a benchmark against future or previous mega-events of the

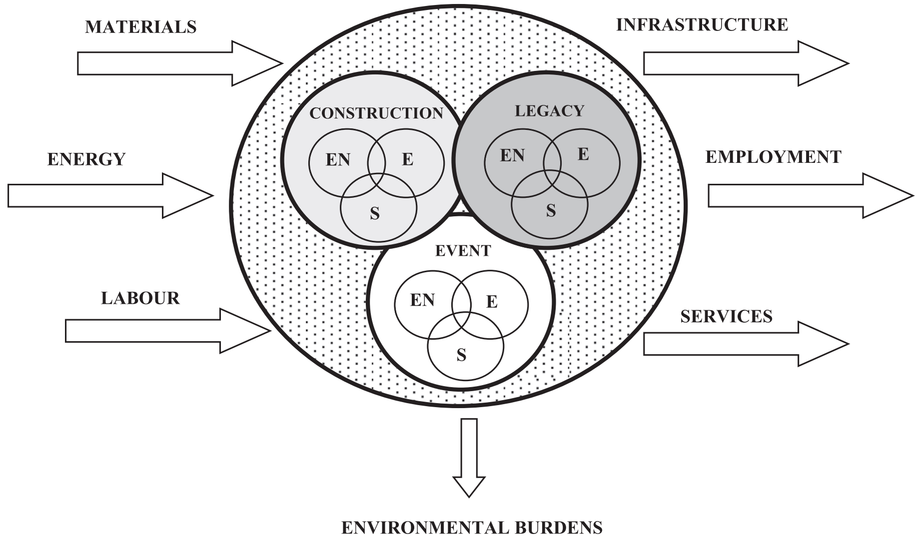

Fig. 1. Schematic representation of a mega-event project as a complex system (E, EN and S are economic, environmental and social aspects) (Parkes et al., 2012).

Table 1
Environmental impacts of a mega-event project included in the proposed framework.

GHG emissions resulting from:	Project phases		
	Construction	Event	Legacy
Water supply & Wastewater removal	X	X	X
Fuel used for transportation (diesel & petrol)	X	X	X
Embodied emissions from construction materials	X		X
Energy used for construction and operation of buildings (gas, diesel & electricity)	X	X	X

same scale. Second, the environmental impacts of the event staging can be minimised by estimating potential emissions resulting from different scenarios, identifying those areas that have the highest impacts (e.g. types of venues with the highest energy consumption) and exploring the options as how to reduce the impacts. Finally, the environmental burdens of the construction and operation of the post-event site alternative design scenarios can be optimised by changing a set of design features defined in the original design specification. In order to explore the robustness of the framework and its practicality as a decision-making tool, it was applied to a case study of the London Olympic Park.

2.3. *Case study — the London Olympic Park*

The data for the construction and event phases used in this work is based on the reports which were regularly published by the Olympic Delivery Authority (ODA) before, during and after the preparation and staging of the event (GLA, 2004; ODA, 2011; London 2012, 2007a,b; 2009).

In order to determine the impacts of different site design scenarios and operation of the buildings in the post-event legacy phase, 3 design scenarios have been developed based on the numerous publications and discussions about possible redevelopment of the Olympic Park (e.g. LLDC, 2012; Cabinet Office, 2013).

2.3.1. *'Business as usual' scenario — BAU*

The 'Business as Usual' scenario is based on the redevelopment plan presented by the London Legacy Development Corporation (LLDC, 2012) which is being implemented in the Olympic Park. It builds on the typical London mixed residential/commercial area with 2–3 storey houses and 4–5 storey apartment blocks. The future area will consist of approximately 11,000 new homes (including the Athletes Village) alongside with education, health and community facilities and 5 Olympic sports venues. 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). The estimated number of different types of new residential and non-residential buildings for each of the three post-event scenarios is provided in Table 2. The estimated floor area for each type of building is provided in Table 3.

2.3.2. *'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 1000 apartments. The rest of the area will be a mixture of different types of commercial offices and small industrial units. It is assumed that the total floor area of all commercial buildings will be approximately 3,000,000 m^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.

2.3.3. *'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-stories 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

Table 2
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	6800	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
Supermarkets	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 3
Estimated total floor area for each type of building for each design scenario.

	BAU scenario	CW scenario	HRHD scenario
Total floor area of all residential buildings (m^2)	638,194	70,000	898,000
Total floor area of all office buildings (m^2)	46,200	2,980,500	2,123,475
Total floor area of all retail buildings (m^2)	22,590	37,650	112,950
Total floor area of all hotel buildings (m^2)	16,800	84,000	168,000
Total floor area of community facilities and social infrastructure (m^2)	76,193	29,488	102,621
Total floor area of all buildings (m^2)	799,977	3,201,638	3,405,046

2,000,000 m^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 development presents an opportunity to accommodate more people in those areas where there is a shortage of land. Detailed explanation of each scenario is provided in the Supplementary Material.

In general, in order to allow a fair comparison of the proposed mega-event site scenarios, a reference scenario should be developed first. A reference scenario should consider pre-event site design taking into account all existing structures prior to the start of the construction phase of a mega-event project. Then, the reference scenario should be compared to a 'Baseline development' scenario, a reference scenario which takes into accounted projected changes of the site design if the event was not held. Finally, all proposed mega-event site scenarios should then be compared to the 'Baseline development' scenario in the absence of the event, in which case the uncertainties regarding the benefits and drawbacks of each scenario will be substantially lower than when comparing the proposed event scenarios only.

However, it has to be noted that in this work the results are presented only for the proposed 3 event scenarios for the following reasons. First, the site of the current London Olympic Park was one of the most desolate and deprived wastelands and, therefore, contained no residential or commercial buildings, hence there were no existing structures prior to the start of the construction phase of a mega-event project to require building a reference scenario. Second, there was no explicit projected plan of changing the wasteland prior to the development of the UK bid to host the 2012 Summer Olympics in London (GLA, 2003). Thus, no clear 'Baseline development' scenario could be defined for this case study.

2.4. Baseline vs optimised scenarios

The data provided in Tables 2 and 3 is presented for the baseline scenarios used in this work. It is assumed that specific design features have been determined for all baseline scenarios. Each design feature is defined as a variable in the mathematical model described in Section 3. However, a set of constraints (minimum and maximum values) is applied to each design feature. The design features for the scenarios are: different types of residential and non-residential buildings; total floor area of each type of building; number of residents, employees and visitors; total amount of building materials used for each building type; visitors' origin types; transport modes and availability of different types of vehicles for the officials during the game period.

Table 4 provides a set of constraints for all types of residential and commercial buildings, which is a minimum percentage of each type of building assumed in the specification for each post-event

Table 4
Assumed minimum compulsory share of each residential and commercial building type for each baseline scenario.

	BAU scenario	CW scenario	HRHD scenario
Residential buildings types (% of the total number of residential buildings)			
Detached house	5	0	0
Semi-detached house	5	0	0
Terraced house	30	0	0
Bungalow	2	0	0
1-bedroom flat	20	40	20
2-bedroom flat	20	10	20
3-bedroom flat	0	0	30
Commercial offices types (% of the total number of commercial offices)			
Type 1 – no canteen, naturally ventilated cellular	3	1	1
Type 2 – no canteen, naturally ventilated open plan	0.3	40	0
Type 3 – with canteen, air conditioned standard	95	25	4
Type 4 – with canteen, air conditioned prestige	0	25	90

Table 5
Assumptions relating to visitors' origin (% of the total number of visitors). Based on 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%

Table 6
Average distance travelled by each type of visitor/official (London 2012, 2007b).

Visitor's/official's category	Average distance travelled – return trip (km)
Visitors origin:	
London	24
UK	330
Europe	2600
Rest of the World (RoW)	15,000
Travel Grant	15,000
Official's type:	
Athletes and families	5000
Media	5000
Officials	7140
Employees and volunteers	40

site design scenario. This will determine the overall consumption of energy and water in buildings during the event and post-event site. Energy consumption in each type of building considered in this study is based on the data from London2012, 2010; HES, 2011; Bohdanowicz and Martinac, 2007; EMSL, 2009; Pérez-Lombard et al., 2007; CIBSE, 2012; Hong, et al., 2013; Tassou et al., 2011; DECC, 2013. Water consumption in each type of building evaluated in this work is based on the data from ODA, 2011; DoH, 2013; Dziegielewski et al., 2000; DfES, 2002; Envirowise, 2002. Emissions conversion factors are based on DEFRA, 2012; DEFRA, 2014 and DEFRA/DECC, 2011. Embodied emissions coefficients for construction materials were evaluated using a life cycle method described in Hammond and Jones, 2008a. It is assumed that the values of emissions conversion factors remain constant throughout the whole project's life lifetime. These values are defined as parameters in the mathematical model presented in Section 3. Complete data is provided in Supplementary Material.

Table 5 defines a set of constraints for visitors' origin travelling to/from the Park during the event and post-event phases. Table 6 provides the assumptions for distances travelled by each type of visitor.

Table 7 provides estimated minimum and maximum transport mode split for all types of visitors and officials during the games period and for all visitors in the legacy period.

Table 8 provides the estimated minimum and maximum values for each type of vehicle available for transportation of the officials during the games period.

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 Development Strategy (London 2012, 2007a) was to transport at least 50% of the total amount of waste and materials by rail and/or water. This objective is incorporated in the model described in Section 3 as a sustainability constraint and applied to all baseline scenarios both in construction and in the legacy phases.

The amount of building materials used for construction of the event venues and infrastructure are based on the data provided in the Carbon Footprint Study (London 2012, 2007b). The amount of building materials use for the construction of the post-event event site are estimated on SPON's, 2013; Monahan and Powell, 2011; Iddon and Firth, 2013; Yan et al., 2010. It is assumed that the following quantities of recycled/reclaimed materials are available for each baseline scenario:

When the transportation distance becomes too long, the overall amount of GHG emissions resulting from the recycled material and the fuel used for its transportation becomes larger than the embodied carbon of the virgin material. Thus, maximum transportation distances of recycled materials are set up as constraints. Table 10 provides maximum distances which are acceptable for the transportation of reclaimed building materials. Embodied carbon for virgin and recycled/reclaimed construction materials is calculated based on Hammond and Jones (2008b).

The sets of constraints described in this section refer to the baseline scenarios based on design specifications summarised in Tables 2 and 3 Once the baseline scenarios have been evaluated the methodology obtains the optimal conditions for each scenario using the model presented in the next section. In the optimised scenarios the following constraints applied for the baseline scenarios have been removed: minimum compulsory share of each residential and commercial building type provided in Table 4; estimated transport mode split presented in Table 7; minimum and maximum number of different types of official vehicles described in Table 8; maximum quantities of recycled/reclaimed building materials available for each baseline scenario provided in Table 9; constraint on the transportation of minimum of 50% of the total construction waste by rail/water; transport modes capacity constraint. Removal of constraints ‘forces’ the optimiser to choose those values for the unconstrained parameters which give the lowest GHG emissions coefficients. For example, the optimiser will select all non-residential buildings to be O1 office type (no canteen, natural ventilated cellular, see Supplementary Material) as this will result in the lowest total GHG emissions. Another example is the choice of transport modes: the optimiser will ‘force’ all visitors from Europe to travel by Eurostar train as this transport mode has

Table 7
Estimated transport mode split for all types of visitors (% of the total in each visitor's category). Based on 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%						

Table 8
Estimated data for the transportation of the officials during the event period. Based on London 2012 (2007b).

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 of vehicles
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

the lowest emissions coefficient of all transport modes available to this visitors' category.

Hence, the results for the optimised scenarios present the lowest theoretical GHG emissions that could be achieved and could serve as a benchmark when comparing different designs for a chosen scenario. Section 4 provides the overall results comparing the baseline and optimised scenarios for the London Olympic Park project. The following section provides mathematical formulation of the model developed for this work.

3. Model formulation

The model solves a single objective optimisation problem where the objective function is to minimise total GHG emissions (*TE*) resulting from the whole life cycle of a mega-event project. The model was implemented in GAMS (2014) 24.0.1 on a 64-bit Windows 8 machine using the CONOPT solver which solves nonlinear optimisation problems using the Successive Quadratic Programming method (Drud, 1992). The problem is formulated as follows:

Minimise *TE*

s.t. *Recycled/reclaimed materials supply constraints*

Transportation modes capacities (1)

Sustainability target constraints

Official vehicles supply constraints

Number of visitors' constraints

Visitors' origin constraints

Building types constraints

Total GHG emissions are calculated as follows:

$$TE = EM + TET + EWE \quad (2)$$

where *EM* is the total amount of GHG emissions associated with all construction materials (often referred to as embodied emissions), *TET* is the total amount of emissions resulting from the transportation of all types of passengers to/from the Olympic Park, *EWE* is the total amount of GHG emissions resulting from the use of energy and water.

The GHG emissions from construction materials are calculated as follows:

$$EM = \sum_{m \in M} \sum_{b \in B} G_{mb} E_m \quad (3)$$

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.

The GHG emissions from transportation are calculated as follows:

$$TET = \sum_{s \in S} ET_s \quad (4)$$

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 as follows:

$$ET_o = \sum_{o \in O} \sum_{f \in F} Y_{of} \ E_o \ F_f \ V_o U_o \quad (5)$$

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 as follows:

Table 9
Maximum quantities of recycled/reclaimed materials available for each baseline scenario.

Amount of recycled/reclaimed materials available (percentage of the total amount of materials)	Baseline scenarios
Steel	10%
Aluminium	20%
Timber	15%
Stone	20%
Brick	25%
Tile	5%

Table 10
Maximum transport distances for reclaimed materials (WRAP, 2008; Hammond and Jones, 2008b).

Material	Distance (km)	Embodied carbon (kg CO_2-eq/kg)
Reclaimed tile	100	0.22
Reclaimed stone	300	0.04
Reclaimed bricks	250	0.04
Reclaimed timber	1000	0.06
Reclaimed steel	2500	0.43
Reclaimed aluminium	2500	1.69

$$ET_c = \sum_{v \in V} \sum_{c \in C} D_c \; E_v \; X_{vc} \; N_v \tag{6}$$

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 are calculated as follows:

$$ET_W = \sum_{w \in W} D_W \; E_W \; Z_W \; A_W \tag{7}$$

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.

The total GHG emissions resulting from the use of energy and water are calculated as follows:

$$EWE = \sum_{s \in S} EE_s + \sum_{s \in S} EW_s \tag{8}$$

where EE_s is the GHG emissions resulting from the 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:

$$EE_o = \sum_{o \in O} P_o \; E1 \; D_e + \sum_{o \in O} Q_o \; E2 \; D_e \tag{9}$$

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:

$$EE_r = \sum_{r \in R} P_r \; E1 + \sum_{r \in R} Q_r \; E2 \tag{10}$$

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:

$$EE_c = \sum_{c \in C} P_c \; E1 + \sum_{c \in C} Q_c \; E2 \tag{11}$$

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 London 2012 (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.

$$EE_n = \sum_{n \in N} C_n \; D_n \; E5 \tag{12}$$

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:

$$EW_o = \sum_{o \in O} \sum_{v \in V} N_{vo} \; W_o \; T_v \; (E3 + E4) \tag{13}$$

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:

$$EW_r = 365 \sum_{r \in R} N_r \; F_r \; W_r \; (E3 + E4) \tag{14}$$

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:

$$EW_c = 250 \sum_{c \in C} A_c \; W_c \; (E3 + E4) \tag{15}$$

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:

$$EWi = (AG \times IG \times NG + I_n) \times E3 \quad (16)$$

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}).

4. Results and discussion

Fig. 2 presents the overall results of the total emissions for the whole project's life cycle for the baseline and optimised scenarios. The duration of the legacy phase is taken to be 25 years.

The optimiser was able to reduce the emissions burden from the baseline scenarios considerably in all three scenarios. In particular, reductions can be seen most strongly in the energy and water and transportation sector. The key variables that changed in the optimised scenarios are types of residential and office buildings and transport modes as the optimiser chose those with the lowest GHG emissions coefficient.

It can be seen (Fig. 2) that the highest GHG emissions occur in the legacy phase for each baseline scenario. 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. In the CW scenario the highest emissions occur from the transportation of visitors, residents and employees in the legacy phase followed by the embodied emissions from construction materials used during the post-event site redevelopment.

Fig. 2 shows that the BAU scenario is the one which has the least environmental impacts in terms of GHG emissions. This can be explained by the fact the total area of the office buildings is almost negligible compared with two other scenarios and the number of the office employees is approximately 5500 compared to 170,860 and 88,220 for the CW and HRHD respectively. Moreover, the majority of the residential dwellings in the BAU scenario are assumed to be semi-detached or terraced houses which results in smaller population density compared to the CW and HRHD scenarios. The highest GHG emissions 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 the legacy phase. This is due to the high number of employees travelling daily to/from the site. The emissions from the energy and water use for the operation of buildings (mostly office buildings) in the legacy phase are almost equal to the amount of embodied emissions from the construction materials use for the post-event site redevelopment.

The scenario which results in the highest total emissions is the HRHD scenario. 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 same categories as in the BAU scenario.

The results for the optimised scenarios show how the total GHG emissions can be minimised if the constraints summarised in Section 3 are removed. It can be seen that the total GHG emissions can be significantly reduced for each design scenario, particularly

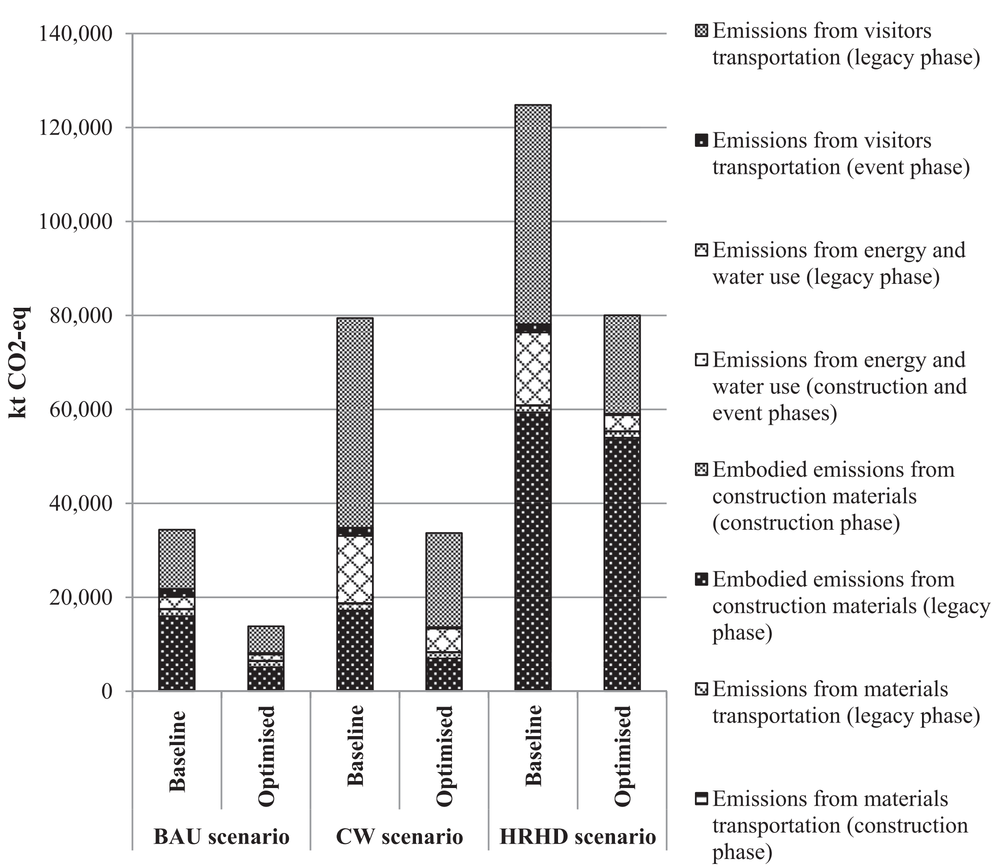

Fig. 2. Total GHG emissions for the whole life cycle of the project – baseline vs optimised scenarios.

for the BAU and CW scenarios.

It is crucial to remember that the 3 scenarios evaluated in this work differ significantly in their design, number and types of buildings and number of on-site residents, employees and visitors. Therefore, total GHG emissions for the whole life cycle of the project presented in Fig. 2 could serve as a metric for comparing baseline vs optimised results for the same scenario but not for comparing between different scenarios. One of the proposed metrics for comparing between different scenarios is the GHG emissions per person (including total site residents, employees and visitors) for the whole lifecycle of the project (Fig. 3). This metric can also be used to compare baseline and optimised results of the same scenario.

It can be seen that the BAU scenario has the lowest GHG per person emissions for both the baseline and optimised scenarios (1.3 and 0.6 tCO_2-eq/person respectively). CW has the highest values for both the baseline and optimised scenarios; however, the value for the optimised scenario is significantly lower than the value for the baseline scenario (4.7 and 1.8 tCO_2-eq/person respectively). The difference between the values for the baseline and optimised HRHD scenario is the lowest of all three scenarios. Another proposed metric to compare between different scenarios is the annual amount of energy (electricity and gas) and resources (water) consumed per person on-site. This metric can also help to set up annual targets on resource and energy efficiency and GHG emissions reduction.

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 whole lifecycle of the legacy phase. However, a significant amount of GHG emissions as well as construction costs could be avoided if a holistic planning approach is adopted at the early stages of a mega-event project. Post-event site redevelopment should be considered right from the start of the event planning and preparation stage in order to determine how the event phase can be transitioned into the next legacy phase. A mega-event site is typically comprised of a number of various infrastructure – event venues such as exhibitions or sports venues; residential houses for delegates, athletes and officials; media or broadcasting centres; restaurants and shops. Systematic planning at the early stages of a project can help to identify how most of the event venues and transport infrastructure can be utilised after the event with minimal environmental and economic impacts.

The London 2012 Olympics is an example of how a holistic approach could be applied to a mega-event project to ensure sustainable long-lasting post-event legacy. Sustainability and legacy have become an integral part of policies and processes since the

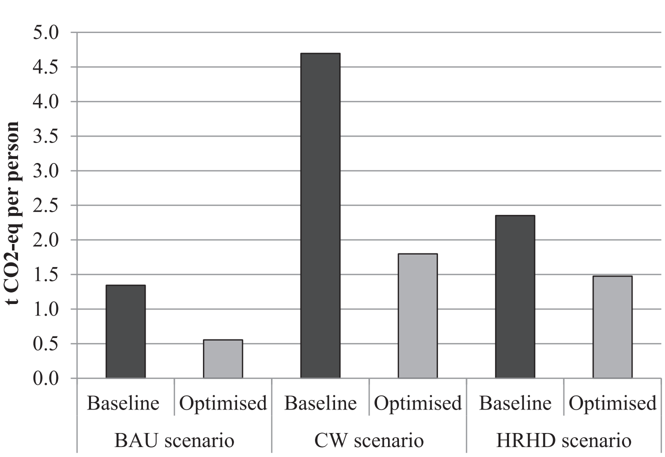

Fig. 3. GHG emissions per person – baseline vs optimised scenarios.

London 2012 Olympics bid, included throughout the design and construction, event and post-event redevelopment phases (LOCOG, 2012). Sustainable Development Strategy was published by the Olympic Deliver Authority in January 2007. The Strategy summarised the legacy plans for the Park and emphasised the importance of maximising the use of permanent event venues and transport infrastructure in the post-event phase (ODA, 2007).

The energy centre, media and broadcast centres, athletes' Village, 5 Olympic sports venues and large transport infrastructure remained on site for the post-event use, which saves almost 2500 ktCO2-eq of GHG emissions associated with construction. Incorporating new sustainable venue designs, using reclaimed and recycling construction materials and installing energy efficiency appliances resulted in further GHG emissions savings of 400 ktCO2-eq during the construction and event phases only (London 2012, 2007b). Thus, applying a holistic approach from the start of a mega-event project planning is essential for minimising environmental impacts and ensuring sustainable long-lasting legacy.

5. Conclusions and future work

This paper presented a novel quantitative framework for evaluation and optimisation of environmental impacts resulting from the whole life cycle of a mega-event project. In the context of the proposed framework, a mathematical model was developed that solves a single objective optimisation problem where the objective function is to minimise the total GHG emissions. The following GHG emissions were considered in this work: emissions resulting from the use of fuel for transportation of all visitors and residents, emissions from the use of energy and water for operation of buildings, and embodied emissions from construction materials. To test the robustness of the proposed framework, the model was applied to a case study of the London Olympic Park. Three potential post-event site design scenarios were developed and evaluated using the proposed methodology: Business as Usual (BAU), Commercial World (CW) and High Rise High Density (HRHD).

The results demonstrated that the highest emissions are attributed to the legacy phase in all scenarios, particularly to GHG emissions resulting from the transportation of visitors and residents, and to embodied carbon from the construction materials. The results for the optimised scenarios demonstrated that the total emissions could be reduced by 30–40% compared to the emissions for baseline scenarios.

The proposed framework can be used as a valuable tool during the planning of mega-event projects. The results of the model can provide the decision makers with important information regarding the environmental impacts of the proposed design scenarios, to help to identify those areas which result in the highest emissions, and to evaluate and benchmark proposed improvements and legacy.

However, planning of mega-event projects is a complex task which involves a large set of stakeholders who often have conflicting interests. Moreover, evaluation and optimisation of economic and social impacts of each design scenario has to be carried out for a holistic sustainability assessment. For example, scenario which has the lowest environmental impacts might not be implemented when numerous economic and social factors are also evaluated and the overall results are analysed by the key stakeholder groups.

The future work will include further development of the mathematical model described in this paper. The model will solve a multi-objective optimisation problem which will include economic and social indicators. The results of the multi-objective optimisation model will provide a 3-dimensional non-inferior Pareto set for each of the proposed design scenarios. By changing the key performance indicators, the model will allow performing an iterative process of sustainability evaluation of multiple scenarios in a short period of times. Future work will also include development of other metrics for comparison between scenarios based on the overall results for social, economic and environmental indicators. Thus, the methodology will serve as a guide for decision making and consensus implementation.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2015.11.009.

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