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Optimised spatial planning to meet long term urban sustainability objectives

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A R T I C L E I N F O

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A B S T R A C T

Urbanisation, environmental risks and resource scarcity are but three of many challenges that cities must address if they are to become more sustainable. However, the policies and spatial development strategies implemented to achieve individual sustainability objectives frequently interact and conflict presenting decision-makers a multi-objective spatial optimisation problem. This work presents a developed spatial optimisation framework which optimises the location of future residential development against several sustainability objectives. The framework is applied to a case study over Middlesbrough in the North East of the United Kingdom. In this context, the framework optimises five sustainability objectives from our case study site: (i) minimising risk from heat waves, (ii) minimising the risk from flood events, (iii) minimising travel costs to minimise transport emissions, (iv) minimising the expansion of urban sprawl and (v) preventing development on green-spaces. A series of optimised spatial configurations of future development strategies are presented. The results compare strategies that are optimal against individual, pairs and multiple sustainability objectives, such that each of these optimal strategies out-performs all other development strategies in at least one sustainability objective. Moreover, the resulting spatial strategies significantly outperform the current local authority strategy for all objectives with, for example, a relative improvement of up to 68% in the performance of distance to CBD. Based on these results, it suggests that spatial optimisation can provide a powerful decision support tool to help planners to identify spatial development strategies that satisfy multiple sustainability objectives.

1. Introduction

Urban planning is being challenged by multiple drivers, including rising populations, increased frequency of extreme events and actions to decarbonise economies to mitigate against a changing climate. By 2030 it is estimated that 60% of the world's population will reside in urban areas, up from just over 50% at present (UNFPA (United Nations Population Fund), 2011). This increased urban population will increase risks to natural hazards over the next century and these will be compounded by extreme events that are expected to increase in frequency as a result of changes in sea level, precipitation, temperature and other climate phenomena (Dawson, 2007; Hunt & Watkiss, 2011; IPCC (International Panel on Climate Change), 2013). However, urban areas are major drivers of climate change, directly or indirectly producing 71% of global carbon emissions (IEA (International Energy Agency), 2008) and are seen as ‘first responders’ at reducing energy and resource usage to mitigate further climatic change (Reckien et al., 2014; Rosenzweig, Solecki, Hammer, & Mehrotra, 2010).

Addressing these drivers of change, and other issues of sustainability more generally, has potential to lead to conflicts and trade-offs as even well intended interventions in one sector can have undesirable impacts on other sectors (Dawson, 2011; Mcevoy, Lindley, & Handley, 2006). For example in the last decade the paradigm for spatial planning policy in Europe has focused almost exclusively on mitigation of GHG emissions through urban intensification (Biesbroek et al., 2010) as denser cities are typically associated with lower transport energy use (Newman & Kenworthy, 1989; Williams, Burton, & Jenks, 2000). However urban intensification has been found to exacerbate urban heat islands, increase flood risk by reducing surface permeability and lead to poor health outcomes for residents (Dawson, 2007; Holderness, Barr, Dawson, & Hall, 2013; Hunt & Watkiss, 2011; Melia, Parkhurst, & Barton, 2012). Furthermore, analysis by Echenique, Hargreaves, Mitchell, and Namdeo (2012) suggest that compact city development results in only minor reductions in travel distances and that these benefits were often outweighed by loss of housing choice, increased crowding and congestion. It is therefore essential that spatial planners avoid making assumptions about the relative merits of compaction and dispersion, and consider evidence about the performance of multiple sustainability objectives, over short and longer timeframes (Campell, 1996; Dawson, 2011).

In the UK, and many other countries, sustainability appraisals within the planning process typically consider these issues in a highly subjective manner with little analytical consideration of the evidence,

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trade-offs and potential synergies between objectives (Gibson, 2006). Traditionally spatial planning decisions have been taken on the basis of 'satisficing' (Simon, 1996) i.e. selecting plans which exceed an acceptability threshold for planning objectives. However, there is a growing body of work that has demonstrated the effectiveness of spatial optimisation techniques to plan infrastructure, such as water distribution networks (Fu, Kapelan, Kasprzyk, Reed, & Asce, 2013; Keedwell & Khu, 2005; Prasad & Park, 2004; Vamvakeridou-Lyroudia, Walters, & Savic, 2005), and transport networks (Bielli, Massimiliano, & Carotenuto, 2002; Delme, Li, & Murray, 2012; Shimamoto, Murayama, Fujiwara, & Zhang, 2010) as well as within land use planning applications (Balling, Taber, Brown, & Day, 1999; Liu et al., 2015; Loonen, Heuberger, & Kuijpers-Linde, 2007; Stewart & Janssen, 2014). Indeed at the scale on entire urban systems, spatial optimisation has been employed to successfully maximise land use compatibility (Cao et al., 2011; Khalili-Damghani, Aminzadeh-Goharrizi, Rastegar, & Aminzadeh-Goharrizi, 2014; Ligmann-zielinska et al., 2005) and in design spatially optimal compact cities (Ligmann-zielinska, Church, & Jankowski, 2005).

Over several decades a number of optimisation algorithms have been adapted and developed for use in the spatial design and planning of infrastructure and urban systems, ranging from the use of relatively simple approaches such as gradient-based and Tabu local search methods (Costamagna, Fanni, & Giacinto, 1998; Jaeggi, Parks, Kipouros, & Clarkson, 2008), through to more complex approaches such as genetic algorithms, which mimic evolutionary operators over a set of solutions to search for optimal solutions to a problem (Konak, Coit, & Smith, 2006; Xiao 2008), particle swarm optimisation which guides a series of solutions through the variable space mimicking the way organisms naturally swarm (Coello, Pulido, & Lechuga, 2004; Poli, Kennedy, & Blackwell, 2007) and ant colony optimisation, which identifies best paths to optimal solutions (Dorigo & Blum, 2005; Yu, Yang, & Xie, 2011); approaches that have been applied to land use allocation studies (Aerts, Eisinger, Heuvelink, & Stewart, 2003; Arthur & Nalle, 1997; Cao, Huang, Wang, & Hui, 2012; Chuvieco, 1993; Liu, Li, Shi, Huang, & Liu, 2012; Liu et al., 2015; Masoomi, Mesgari & Hamrah, 2013; Qian, Pu, Zhu, & Weng, 2010; Stewart, Janssen & Herwijnen, 2004).

However, to date the use of spatial optimisation to tackle multiple real world sustainability objectives from a broad spectrum of long-term sustainability issues (risk prevention, mitigation of transport emissions etc.) in applications that closely resemble the planning decisions faced in the future with regard to sustainable development of urban systems has been somewhat limited (Keirstead & Shah, 2013). Indeed previous research has primarily focused on obtaining optimal land use allocations (Cao et al., 2012; Qian et al., 2010), but in the absence of an appreciation of real-world risks faced by urban systems in the future, such as climate change induced heat and flood hazards (Reckien et al., 2014).

To address this sparsity in the evaluation of multiple real world sustainability objectives within the spatial planning of new development this work develops a spatial optimisation framework based around resource allocation; an approach that complements the 'evolutionary' approach 'to planning sustainable urban areas' (Ligmann-zielinska et al., 2005). The framework is novel in that it couples simulated annealing, an approach that has been found to be computationally efficient for high-dimensional spatial optimisation problems (Duh & Brown, 2007) and a proven ability in resource applications (Aerts & Heuvelink, 2002; Sidiropoulos & Fotakis, 2009), with Pareto-optimisation (Xiao, Bennett, & Armstrong, 2007), such that comparisons can be undertaken rapidly and in a straight forward manner between the optimal spatial solutions found for different combinations of multiple sustainability objectives. A case study, applied to Middlesbrough Borough Council a local authority area in the North East of England (Fig. 1), demonstrates how spatial Pareto-optimisation based on a simulated annealing framework (Kirkpatrick, Gelatt, & Vecchi, 1983) can be employed to derive spatial development patterns that are sensitive to climate induced hazards such as heat and flood whilst accounting for current planning policies that seek to avoid fragmented urban growth and development on green space. This multi-objective spatial Pareto-optimisation approach comprises three main steps:

(i) Define the set of sustainability objectives that are to be optimised within the framework (Section 2.1);
(ii) Apply a simulated annealing algorithm to generate spatial configurations of new development that meet the sustainability objectives (Section 2.2);
(iii) Use a sorting procedure to extract the Pareto-optimal sub-set of solutions that perform better than all tested solutions in at least one of the sustainability objective outlined (Section 2.3).

Section 3 presents the results of a case study in Middlesbrough in the UK, identifying optimal locations of development before outlining the

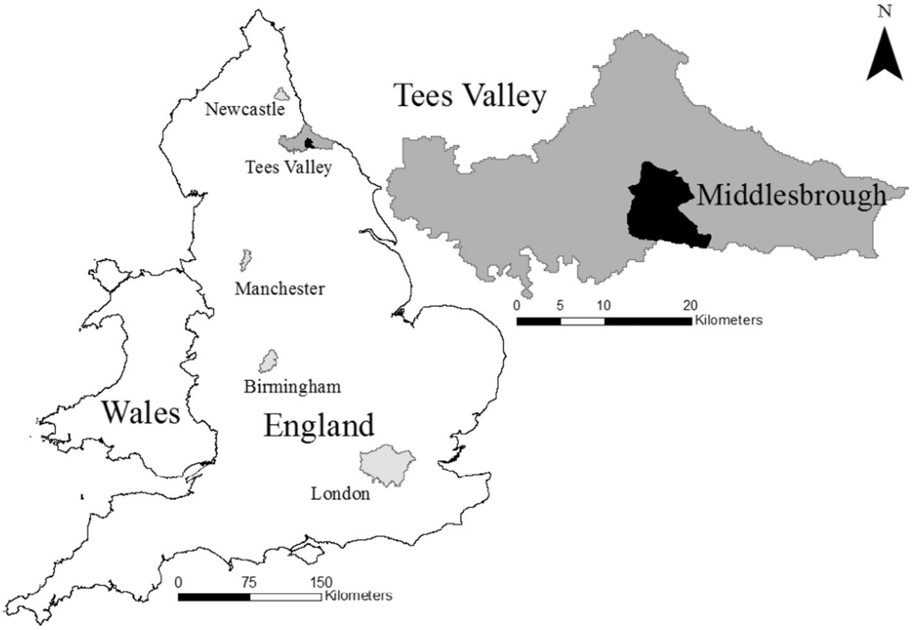

Fig. 1. The case study area of Middlesbrough within the Tees Valley.