Environmental Modelling & Software 101 (2018) 146–168

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

An integrated optimisation platform for sustainable resource and infrastructure planning

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ARTICLE INFO

Article history:
Received 4 March 2017
Received in revised form
8 November 2017
Accepted 16 November 2017

2010 MSC:
97M10
92D40
90C11
91B69
93A30
93B40

Keywords:
Integrated Environmental Modelling (IEM)
Decision support
Sub-Saharan Africa
WASH
Agent-Based Modelling
Mathematical Programming

ABSTRACT

It is crucial for sustainable planning to consider broad environmental and social dimensions and systemic implications of new infrastructure to build more resilient societies, reduce poverty, improve human well-being, mitigate climate change and address other global change processes. This article presents *resilience.io*,[2] a platform to evaluate new infrastructure projects by assessing their design and effectiveness in meeting growing resource demands, simulated using Agent-Based Modelling due to socio-economic population changes. We then use Mixed-Integer Linear Programming to optimise a multi-objective function to find cost-optimal solutions, inclusive of environmental metrics such as greenhouse gas emissions. The solutions in space and time provide planning guidance for conventional and novel technology selection, changes in network topology, system costs, and can incorporate any material, waste, energy, labour or emissions flow. As an application, a use case is provided for the Water, Sanitation and Hygiene (WASH) sector for a four million people city-region in Ghana.

Software/data availability

The *resilience.io* WASH model was built by Charalampos P. Triantafyllidis, Xiaonan Wang, Koen H. van Dam, Kamal Kuriyan and Nilay Shah from Imperial College London with data and technical support by Rembrandt Koppelaar, Zoltan Kis and Hannes Kunz from the Institute of Integrated Economic Research. The platform is designed for open-source future release by using only open-source software. A beta-version of the platform is available upon request from the authors including the data-set to reproduce the presented use case. The platform is of approximately 800MB in size on a Windows-based machine. Further details concerning the hardware/software used can be found in Table 3.

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https://doi.org/10.1016/j.envsoft.2017.11.034

1. Introduction

Several modelling techniques have been proposed to gain insights in the delivery of sustainable goals in a scientific manner. Recently, water quality performance assessment has been under the microscope (Massoudieh et al., 2017). Furthermore, in (Alhamwi et al., 2017) a GIS-based platform was introduced to facilitate storage and flexibilisation of technologies in urban areas. In (Cominola et al., 2015) the need for models that describe exogenous drivers affecting water and demand management was highlighted, to inform strategic planning and policy formation, while various platforms were also presented (DeOreo et al., 1996; Kowalski and Marshallsay, 2003; Froehlich et al., 2009; Beal et al., 2010). In (Hu et al., 2015) multi-threaded programming with Hadoop-based cloud computing was used to implement a Multi-Agent System for environmental modelling. Furthermore, in (Berglund, 2015) Agent-Based Models (ABMs) are reviewed in the context of water management planning decisions.

The benefit of planning based on advanced system models lies in the ability to rapidly carry out project evaluation within a complex city systems perspective. Such models can remove the divide between high-level master-planning and isolated low-level project planning, by enabling a link of feedback between the two, the exploration of more options and trade-offs, and enhanced visibility on positive and negative impacts in multiple-dimensions, thus lowering the risk and cost of planning. Key is not to rely on a pure techno-economic planning approach (e.g. reductionist infrastructure cost estimates), since sustainable development, social parameters and cost and benefits are inextricably bound together (White and Lee, 2009).

Concerning the presented use case application, models focusing on specific components of the water cycle are various and include agent-based water demand models with attitudes, norms, and behavioral control towards water use (Koutiva and Makropoulos, 2016), Linear Optimisation (LO) models for water supply pipe networks (Sarbu and Ostafe, 2016) and sewer pipe networks (Safavi and Geranmehr, 2016), Mixed-Integer Non-Linear Programming (MINLP) approaches for pipe network optimisation (Moeini and Afshar, 2013; Afshar et al., 2015), groundwater and rainwater storage and network MINLP (Chung et al., 2009), Mixed-Integer Linear Programming (MILP) model based water treatment technology planning including energy use estimations (Alqattan et al., 2015), and water-reuse potential estimations using a MILP architecture (Liu et al., 2015).

Complete water system models are less common, a class referred to as Integrated Urban Water Cycle Models (IUWCMs) when including all water cycle aspects, and Integrated Urban Water System Models (IUWSMs) that also integrate social, environmental, economic, and other resource flows like energy (Bach et al., 2014). Based on a literature review from 1990 to 2015 a total of fourteen existing IUWSMs were documented (Peña-Guzmán et al., 2017), although some, upon evaluation, appear to be misclassified given their too narrow usability, such as the commercial Aquacycle tool that focuses on rain and storm-water modelling (Sharma et al., 2008), or the commercial MIKE Urban software package for hydrology and flood modelling (Berggren et al., 2012). Social elements were covered in one out of fourteen models (De Haan et al., 2013), and five allowed for energy and emissions.

The two most complete IUWSM models were found to be WaterMet2 (Behzadian et al., 2014b) and Urban Water Optioneering Tool (UWOT) (Rozos and Makropoulos, 2013). WaterMet2 is an open-access difference-differential equation simulation model that integrates both natural and human water and wastewater systems inclusive of four different scales: indoor, local, catchment and city areas. These include the ability to model water demand and supply balances, pipeline fluxes, energy requirements and greenhouse gas emissions (Behzadian et al., 2014a). UWOT is an, available on request, spatially fixed fine-grained minute to hour appliance household demand model with aggregation to neighborhood and city scale. Supply is spatially solved using genetic algorithm optimisation of a pre-defined treatment plant and pipe network for water flow allocation. The platform is built in Simulink/MATLAB linked to a technology and pipeline network library database (Rozos and Makropoulos, 2013).

The main limitation of these tools is their rigidity as their goal is to analyse the performance of a user designed WASH technology-network system inclusive of any future interventions. This as opposed to starting with performance criteria as constraints on the system, including economic, environmental and social requirements and using the tool to explore urban water system design solutions that fall within the desired performance to meet future urban water cycle needs.

The gap we attempt to bridge with this platform is therefore the following: since technological innovation and planning is arguably crucial to achieve sustainable development (Anadon et al., 2016), how can technical tools assist in i) exploring planning solutions and providing the quantitative evidence on meeting the broader economic, social and environmental requirements for implementing technological investments on the ground and ii) bring *learning* and engagement of stakeholders in the full development cycle of such tools?

The first part is materialised by a systems modelling scheme; we embrace the *assemblage approach* by combining polished and well-established modelling formalisms including Agent-Based Modelling and Mathematical Programming. ABMs are becoming more and more popular in Environmental Modelling (Sun et al., 2016) and at the same time Mathematical Programming has seen enormous progress in the development of polished, consistent and accurate solvers across the latest two decades while also being one of the most widely used tools to inform transparent decision making. The intention of this approach is as analysed in (Voinov and Shugart, 2013) to allow models to exchange communication on run-time as an integrated suite which outputs meaningful results and can potentially answer an array of questions that decision makers are interested in.

The second part is effectively achieved by the open-access development cycle of the platform. A major degree of involvement by potential users and stakeholders across a variety of disciplines took place to elaborate on the optimal design, implementation and usefulness of the platform while not over-complicating the models. By conducting a series of communication exchanges with local experts in Ghana from various institutions (e.g. Ghana Water Company, University of Ghana, etc.), and delivery of an early version for testing, we tried to shape the platform to best serve the user needs to assess policy implications so as to reach sustainability targets in the most realistic manner.

This article is organised as follows: in section 2 we present the modelling techniques built-in to the platform. In section 3 we describe the link between the models and the input data, and the associated mechanisms as well as the major implementation details. Section 4 demonstrates a series of questions that can be potentially answered by using *resilience.io*. Section 5 presents the WASH sector use case as a first application as well as the context