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Smarter urban metabolism: Earth systems re-engineering

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The archetypal metabolism of the city is defined by the flows of energy and materials (carbon, nitrogen, phosphorus, water) entering the city from the rest of the global economy, then circulating around and through its economic, social and industrial life, before returning to the city's environment (and the global economy). Salient in realising a smarter urban metabolism is the change in viewing nutrients not as pollutants – a perception entailed in the historic success of water-based systems for securing public health in cities – but as resources to be gainfully recovered. In order to explore the scope and feasibility of such (radical) change, a computational multi-sectoral systems analysis procedure has been developed and applied to case studies of Atlanta, USA, and London, UK. Starting with an expression of what might constitute a more benign, climate-repairing future for the interaction between these cities and their environments, multi-sectoral systems analysis is used to examine aspects of the economic feasibility and then social legitimacy of candidate policy interventions and technological innovations for attaining such a future. In particular, the notion of a privileged, non-foreclosing innovation or intervention is introduced and illustrated.

1. Introduction

Until public health had been secured for citizens living cheek by jowl in the confined spaces of cities, cities were arguably prevented from realising their full potential as the engines of national (and now global) economies (Glaeser, 2011; McGreevey *et al.*, 2009). One hundred and fifty years ago – when the introduction of the water closet (WC) was becoming widespread – the configuration of the water infrastructure, into which most cities of the global north were to become ever more comprehensively locked, could not readily have been imagined (except perhaps by those with a good knowledge of ancient civilisations; Angelakis *et al.* (2012)). Not until just some two decades ago was the question raised as to whether the predominant style of environmental engineering of such infrastructure, especially that for managing wastewater (on the 'downside' of the city), was self-evidently 'doing good by the environment' (Niemcynowicz, 1993). If it was not, moreover, how might it be possible to re-engineer a way out of this technological 'lock-in' and to learn how to avoid it in the first place, from socially and economically successful cities of the global south (Beck, 2011; Crutzen *et al.*, 2007)? We stand presently on the threshold of what some, therefore, are calling a decisive change of paradigm (Larsen *et al.*, 2009, 2013).

In the fullness of time, that small, seemingly humble, yet utterly vital innovation of the household WC has indeed brought about its own form of earth systems engineering. Consider this: the WC, together with subsequently evolved sewerage, cuts the short feedback loop between pathogenic excretions and drinking water and conveys citizens' (human) metabolic residuals out of the confined spaces of the city and into the environment. The materials we need in food for sustaining ourselves – nitrogen (N), phosphorus (P), carbon (C) and so on – pass through our bodies and, given the WC, are then headed to some form of aquatic environment. Prior to comprehensive installation of the WC and sewerage, this was not naturally so. Public health in the city has been acquired at the expense (largely) of surface water pollution. Thus did (and does) the environmental engineering of the city's wastewater infrastructure progress through eras driven successively by the need to control pathogenic pollution, gross organic pollution, nutrient pollution and toxic pollution – all in respect of water bodies. Had the Reverend Moule's earth closet (EC), or some kind of vacuum closet (VC) (Geels, 2006), instead gained supremacy ahead of the WC popularised by Mr Crapper, might none of these eras of *water* pollution control ever have been entered into.

From another perspective, given the extraordinary success of the Haber–Bosch process for manufacturing fertilisers based on nitrogen (Erisman and Larsen, 2013; Erisman *et al.*, 2008), the WC and sewerage – in the absence of their effective coupling with wastewater treatment – have participated in fuelling coastal eutrophication on a global scale (Beck, 2011; Grote *et al.*, 2005). Artificial fertiliser is applied to the land, to produce foodstuffs in North America, for example. These products are shipped around the globe, to become imports into, say, Asian countries and their cities. There, once consumed, and in the absence of wastewater treatment – installation of which component of infrastructure tends to lag some 20 years behind the introduction of infrastructure for potable water supply on the 'upside' of cities (McGreevey *et al.*, 2009) – all the residuals of the nutritious nitrogen and phosphorus materials end up (untreated) in coastal seas and oceans, with distorting consequences for the structures of marine ecologies and their associated fisheries (Jackson *et al.*, 2001). Moreover, given the current staggering successes of membrane technologies, hence the burgeoning of desalination facilities around the world (Frenkel and Lee, 2011), there is every prospect of yet more earth systems engineering being wrought – and with complex, unfolding, unravelling social consequences. For desalination amplifies the capacity for supplying potable water to people in coastal cities. In principle, this greater access to water should sustain greater populations of citizens in such cities, all of whom may thereby be placing themselves increasingly at risk from the threats of sea-level rise (Beck, 2011).

There are many reasons, therefore, to judge that we stand on the threshold of constructive, pivotal change: change that might best propagate from beginnings in the human environment (local and very personal scale), through infrastructure and the built environment (city-wide scale), hence eventually to better stewardship of the natural (and global-scale) environmental component of coupled human-built–natural systems. This would be change, therefore, of proportions entirely consistent with the scale and scope of earth systems engineering, conceptually defined by Allenby (2000) as

> [T]he study and practice of engineering human technology systems, and related elements of natural systems, in such a way as to provide the required functionality while facilitating the active management of the dynamics of strongly coupled fundamental natural systems. We have been doing [this] for a long time, albeit unintentionally. The issue is whether we will assume the ethical responsibility to do [Earth Systems Engineering] rationally and responsibly.

The global consequences of the mass introduction of the highly local device of the WC during the nineteenth and twentieth centuries exemplifies such 'unintentional' earth systems engineering. It would be encouraging to think that the like introduction of membrane technologies in the twentieth and twenty-first centuries would have more of the reflexive qualities of the earth systems engineering Allenby is today urging upon us.

The change advocated in this paper is that towards what is labelled as 'smart urban metabolism'. It entails essentially a change in mindset: from viewing the carbon, nitrogen, phosphorus and other materials entrained into the water metabolism of the city (as a result of the WC) as pollutants to be rid of, at a cost, to their being viewed as resources to be recovered – with profit (Beck *et al.*, 2012). Changes of personal dietary and sanitation habits, the introduction of novel household plumbing devices (urine separating toilets (USTs)) and the local recovery of nutrients (nitrogen and phosphorus) in neighbourhoods, districts and cities, can all have global ramifications: for the thereby substituted carbon-energy footprints of first-manufacture nitrogen-based fertilisers (through the Haber–Bosch process) and first-extraction phosphorus-based fertilisers, and like footprints of their subsequent (global) transport from sites of manufacture and extraction far distant from the given city.

Section 2 presents a working definition of smartness about urban metabolism and discusses its role in earth systems re-engineering. Here, *re*-engineering emphasises now the self-aware aspects of earth systems engineering, as opposed to their previously unintentional nature (as Allenby (2000) has put it). In many ways, introduction of the UST might come to epitomise such contemporary *re*-engineering, when set notably in the context of the pervasive infrastructure that has followed from the popularisation of the WC in the mid-nineteenth century. Considerations of what constitutes environmental benignity in the behaviour of the city are uppermost in Section 2. The multi-sectoral approach to exploring how such smart urban metabolism might be acquired is the subject of Section 3. Section 4 addresses matters of foresight: which, among the many possible technological innovations and policy interventions, might be key to liberating the sparks of economic feasibility that motivate the changes advocated? Specifically, the potential of several candidate innovations for sparking multi-sectoral change within the city-watershed systems of Atlanta, USA, and London, UK, is examined. Some of the interventions bear the prospect of being more socially disruptive (and others less so). And when the foresight of 'who pays' and 'who gains' is set out for all in the community of stakeholders to contemplate, the social legitimacy accorded to any one immediately actionable intervention becomes paramount. These facets of the human–social dimension of smarter urban metabolism, then, will occupy the discussion of Section 5.

Overall, the authors' purpose is to circle around the challenge of achieving smarter urban metabolism (within the context of earth systems re-engineering) from the perspectives of environmental benignity, then economic feasibility, and finally social legitimacy – in other words, from an account of sustainability according to the triple bottom line (TBL) (Elkington, 1998). The central threads of the paper's argument are those of technological innovation and the multi-sectoral model, which will be introduced in Section 3.

2. Smarter urban metabolism: cities as forces for environmental good and climate repair

Cities are nodes of concentrated, intensively manipulated and deeply intertwined global flows of resources. Understanding the city's metabolism, hence its re-design, re-engineering and less unsustainable stewardship, may be approached from a variety of perspectives – in fact, from as many perspectives as there are industrial–economic sectors and species of materials–energy participating therein.

The authors' background, it hardly needs saying, is that of urban water infrastructure. And it is commonplace today to read and hear of a 'global water crisis' – evidence indeed of the success of two decades of effort to push the subject of water towards the top of the global political agenda. Yet such talk tends to limit thinking about the city's water infrastructure to matters of water supply, water recovery and water re-use (Beck and Villarroel Walker, 2011). It accords inadequate, if not scant, recognition to the role and place of wastewater in that infrastructure – or rather the 'waste' in the water (Beck, 2011; Beck *et al.*, 2011).

Others, approaching the big picture from different disciplinary backgrounds, do their like bit for their focal interests. None of us is entirely above trying to grab the headlines of scientific and public attention, hence to champion the cause of our discipline. For some, the twenty-first century will be a 'nitrogen economy' (Erisman and Larsen, 2013; Erisman *et al.*, 2008). For others it will be the century in which 'peak phosphorus' (Cordell, 2013; Elser and Bennett, 2011), or 'peak food' (Brown, 2011), will render 'peak oil' a mere bump in the global economic superhighway. Telling here, of course, is the fact that these calls for greater attention to the otherwise under-appreciated global nitrogen and phosphorus cycles resort to drawing parallels with the (self-evidently) much better appreciated energy sector and its companion global carbon cycle.

The change advocated, from nutrients being treated as pollutants to their being viewed as beneficial resources, seems 'smart' enough in itself alone. Yet given now an altered apprehension of the city's metabolism – as not being solely (in the authors' case) that of water fluxes, but that of the multiple carbon, nitrogen, phosphorus, energy, water and other material fluxes – a further change of outlook becomes necessary: from policy and engineering analysis of the water sector alone, to that of *integrated* analysis of the water *and* nutrient *and* energy sectors (Villarroel Walker and Beck, 2012; Villarroel Walker *et al.*, 2012). This too will be smartness in the urban metabolism. It is an outlook entirely in line with the emerging global agenda item of the 'water–food–energy–climate nexus' (Hoff, 2011), itself the subject of a book from the World Economic Forum (WEF) (WEF, 2011). Yet even there (in the WEF book), one sector, one material, is given precedence: the multi-sectoral nexus is subordinated to the book's primary title of 'water security' (WEF, 2011). And perhaps this is quite appropriate. For water, it may be argued, is *primus inter pares*, if for no other reason than that it is the only material–energy flux onto, into, across and through the city whose behaviour (in significant part) is 'stochastic', with a frequency spectrum not confined solely to the predominantly 24 h–7 d frequencies of the complementary, more predictable, hence 'deterministic', socio-economic life of the city. Fast, transient precipitation events and droughts occupy frequencies outside the (anthropocentric) 24–7 bandwidth, where use of the word 'frequencies' has to do with the predominant sinusoidal oscillations of which a time-varying signal (or component of a system's dynamic behaviour) is composed, not the frequency with which any event is deemed to recur.

This distinctive feature of the city's water metabolism notwithstanding, the point is this. Adopting a singularly focused mono-sectoral approach to understanding and engineering re-design for a smarter urban metabolism will not be adequate. Put rather more dramatically, a singular focus on attaining low-carbon infrastructure in the UK could inadvertently imply technological changes – and earth systems re-engineering – requiring massively more imports of lithium (within just 5–10 years into the future) than current total UK imports thereof (Purnell *et al.*, 2012). The scenarios for such C-focused developments likewise imply massive relative flows into the country of rare-earth elements, which might simply not be available, for a host of geological and geo-political reasons (Purnell *et al.*, 2012).

Put colourfully, we are all familiar with 'growing green'. Now there is considerable interest in 'growing blue' (Auguste, 2012), as in water-sensitive economic development (and as also originating in the WEF). Others, no doubt, could argue in favour of growing yellow (for nitrogen; Erisman *et al.* (2008)) or growing red (for phosphorus; Elser and Bennett (2011)) and so on. Herein, however, the argument is for 'growing rainbow', albeit with water – or carbon, or energy (arguably) – treated as *primus inter pares*, that is, as the most expedient short-cut to achieving rainbow-growth.

By smarter urban metabolism, therefore, smart is intended primarily in the sense of *not* labouring under the poorly informed limitations of a mono-sectoral perspective. Smarter will also be a function of thinking and analysis that effectively embrace material–energy fluxes operating over possibly vastly different spatial scales: literally from the intensely personal and local, for example, dietary choices, to the global, as in the extraction of fertiliser ore in one country and its transport and application to the land in another. Addressing such cross-scale interactions is indeed one of the hallmarks of earth systems engineering (Walsh *et al.*, 2012). Just as smart, if less self-evident, will be thinking and analysis spanning very different scales in time: both strategically (i.e. consistent with sustainable development over the decades) and very rapidly, over a matter of hours and minutes. Again the work of Walsh *et al.* (2012) is exemplary, in respect of their integrated assessment of the strategic urban impacts of long-term climate change on short-term transient extreme events, such as storms and heat waves. This might be termed 'full spectrum' thinking and analysis. Smart, understood as highly informed, highly intelligent, quasi-real-time control of urban metabolism, is not intended in this paper.

In short, the word integration comes to mind as a synonym for smartness (or resilience, or sustainability, for that matter). Integration is to be achieved over multiple sectors, multiple spatial scales (in particular), and over the multiple, constituent frequencies of which any system's unsteady-state dynamic behaviour is composed. Many indeed are the contemporary calls for adopting more integrated, better joined-up approaches to re-engineering cities in the light of climate change and the quest for greater sustainability (Allenby, 2012; Beck and Villarroel Walker, 2011; Fink, 2012; Hall *et al.*, 2012).

Last, it is observed that subsumed under this working definition of smarter urban metabolism are three related, complementary, amplifying notions, as follows.

(*a*) Eco-effectiveness: progressive re-design of technological systems (especially within the city) according to the principle of 'waste equals food' (McDonough and Braungart, 2002; Villarroel Walker *et al.*, 2012), which implies less linearity (once-through) and more circularity of urban resource flows, that is, recycling (if not 'upcycling', wherein the quality of the resource flow improves the more times it is recycled).

(*b*) Cities as forces for good in the environment: re-engineering of the city's infrastructure such that the city not only restores lost ecosystem services, but also becomes a net generator of them, both within the landscape of the city and in its surrounding environment (Beck *et al.*, 2010; Beck, 2011).

(*c*) Cities as 'geo-engineering building blocks' or – perhaps better put – cities as 'forces for climate repair' (Fink, 2012), so that they are not only resource-recovering but also greenhouse gas (GHG)-emission-suppressing, even GHG-absorbing (as in the production of algae, hence biofuels, from wastewater and waste gaseous emissions from power stations).

3. Multi-sectoral systems analysis

This approach of MSA is integrated in the sense that it covers multiple economic/infrastructure sectors (and multiple material–energy flows) and stands, therefore, in contrast to the majority of previous materials flow analyses (MFAs) (Antikainen, 2007; Lang *et al.*, 2006; Schmid Neset *et al.*, 2008). Its spatial scale is essentially solely that of the city-region (or watershed), *ergo* not remarkably integrated along that dimension. Likewise, among the spectrum of seconds, minutes, hours, days, weeks, months, years, decades and so on, MSA is somewhat singularly confined to year-to-year changes, hence far from a reflection of full-spectrum analysis (which has been addressed elsewhere and with a different, complementary modelling framework; Beck *et al.* (2010)).

Details of the content and application of MSA can be found elsewhere (Villarroel Walker and Beck, 2012; Villarroel Walker *et al.*, 2012). In outline, the basis of the MSA is the set of MFAs, that is, simple mass balances and a simple procedure of accountancy for the flows of materials among a set of unit processes (or sub-systems) under steady-state conditions, indicative of annual average properties of the system and its many sub-systems. At a macroscopic level, the chosen city–watershed system comprises essentially the five economic/industrial sectors of water, energy, waste-handling, food and forestry. This set of five sectors interacts with other relevant systems through imports and exports of materials, as well as with the air, water and land environments (or atmosphere, hydrosphere and lithosphere, respectively). Typically, one supposes the city is engaged in emitting pollutants to these three environments. In the case of GHG emissions, these will accordingly be accounted for as specific fluxes of carbon and nitrogen compound species. In addition, the five sectors subsume, to some extent, the transport sector, as in the import and use of vehicle fuels, and the construction sector, where wood products are used for construction (as is significantly the case for Atlanta).

This model (the MFA, or ***M***) has five state variables: water, energy, carbon, nitrogen and phosphorus. In other words, each flux between unit processes and sub-systems within the five sectors is characterised by a vector of five elements. Unit processes are typified by technologies such as incineration or (microbial) anaerobic digestion, as well as the transformations effected in a household, such as the preparation and consumption of food. The structure of the MFA model is thus defined by

(*a*) the logic of the connectivity of fluxes of material-energy among unit processes and sub-systems
(*b*) biochemical transformations in a given unit process, represented (in general) by relatively simple non-linear algebraic expressions (for the kinetics or stoichiometry of reactions).

The parameters ($\boldsymbol{\alpha}$) of these input–output transformations across any sub-system, as well as consumption patterns (e.g. diet), physical attributes (e.g. cloud cover) and partition coefficients, are considered to be uncertain, with uniform probability density functions between their specified upper and lower bounds. The application of new policy or the introduction of candidate new technologies – for instance, the production of algae from wastewater (AWW) – amounts to changes in the connectivity and/or material–energy transformations in the structure of the model, as well as changes in its parameterisation.

In order to gauge the metabolism of the city–watershed system as a whole, for better or for worse (in respect of the environment), MSA calculates various numerical criteria, covering resource consumption, generation of beneficial products and the emission of wastes, as formal expressions deriving from the principles of eco-efficiency and eco-effectiveness (Villarroel Walker, 2010; Villarroel Walker *et al.*, 2012). Such criteria allow cross-comparisons to be made between the present status of the system and any future status, with (or without) the various candidate policy and/or technological innovations.

The whole of the MFA model is embedded within a Monte Carlo simulation (MCS) framework. The MCS in turn forms a part of a regionalised sensitivity analysis (RSA) (Hornberger and Spear (1981); see also Osidele and Beck (2003), in more advanced form). The MSA software, therefore, comprises the MFA model and the MCS and RSA procedures. All of the current study's policy assessments and technology screening are thus conducted under uncertainty, which uncertainty may (in the event) be sufficient to render statistically insignificant any differences between present/future status and the presence/absence of a technological/policy intervention.

MCS is used for the familiar, forward, scenario, 'what if?' types of analyses. The RSA performs a form of inverse, backward or back-casting analysis: 'what are the promising interventions?', it enquires (as it were), for achieving a given target/behaviour. To illustrate the nature of this analysis, suppose current arrangements of the city–watershed system are such that X thousand tonnes of carbon are being emitted to the atmosphere, or that overall the system's eco-effectiveness is attaining a value of Y. Under consideration is a future target performance of, say, at least a 30% reduction/improvement in either of these measures, such that (desired) future behaviour is at most $0{\cdot}7X$ (or at least $1{\cdot}3Y$). This behaviour is here labelled as B and its complement, in other words, future performance of more than $0{\cdot}7X$ (or less than $1{\cdot}3Y$), as not-the-behaviour NB. Suppose now that a set of candidate technology or policy interventions is under consideration, such as UST or AWW (and so on), which are numerically encoded in the parameterisation ($\boldsymbol{\alpha}$) of the MFA model. Expressed thus, and under (gross) uncertainty (including that attaching to $\boldsymbol{\alpha}$), the RSA allows identification of those parameters that are key to determining whether B or NB is attained, say the subset of parameters $\boldsymbol{\alpha}_{\text{key}}$, and those that are redundant to such discrimination. Of special significance is whether any of the candidate technological (or policy) interventions are found to be members of the vector $\boldsymbol{\alpha}_{\text{key}}$.

3.1 Foresight and the triple bottom line

The MSA computations may be considered as a procedure for generating foresight (Beck, 2002, 2005; Beck *et al.*, 2002; Osidele and Beck, 2003). The intent is to circle around the challenge of achieving smarter urban metabolism, something self-evidently having to do with {environmental benignity} within the accountancy of the triple bottom line. In the following, application of the MSA in Section 4 focuses on matters of {economic feasibility}. Section 5, in anticipating future work, will address how MSA might be employed to explore (and in practice support) governance for investing the interventions that are made with greater {social legitimacy}. In some senses, Section 4 is concerned with identifying the economic sparks of possible change, while Section 5 begins to examine what kind of social governance might enable those sparks to be gathered into igniting actual change in practice – perhaps a kind of mass 'buy-in' to the vision of smarter urban metabolism.

Through the RSA procedure, more specifically, the search is for what might be the key technologies enabling the possible realisation of a smarter urban metabolism (in Section 4). In Section 5, the authors conjecture on how to address the social and human dimensions of plural and contested visions for the future – and plural and contested perspectives on what constitutes the science (and economics) underpinning the acquisition of foresight. In doing so, the results of Section 4 are drawn upon to illustrate the potential benefits of being able to identify what is here termed a 'privileged, non-foreclosing' technology or policy intervention.

4. Computational results: key interventions to attain multiple resource-recovering targets

In 2010, about 5·45 million people were living in the Atlanta metropolitan area (AMA), which occupies roughly 22 000 km^2. The Greater London area (GLA), in comparison, has a population of 7·8 million and occupies just 1570 km^2. The population of Atlanta has grown by 100% since 1985, London's by 15%. The proportion of land use classified as 'urban' in the GLA has fluctuated between 57% and 62% over the past 25 years, while that of the AMA was projected to increase from 20% in 1987 to 34% in 2010 (Hu, 2004). Food consumption by the two populations is estimated to be 0·6–0·8 t per capita each year in the GLA and 0·8–1·4 t per capita in the AMA. Densely populated London is served entirely by a conventional, centralised sewerage and wastewater infrastructure, whereas almost 40% of metro Atlanta's population occupies dwellings utilising septic tanks, *ergo* a decentralised arrangement. Both are locked into the prevailing mind-set of nutrients-as-pollutants.

The present authors' stance, as currently bystanders to any actual debate in either city, is this: what might it take to create value in the nutrients as recoverable resources? How, for instance, should a smarter urban metabolism be achieved, including (in part) some suppression of GHG emissions, through the recovery of biofuels by way of the production of AWW? In short, the future target behaviour definition (*B*) of the MSA is composed of multiple goals for resource savings and recovery, as follows

(*a*) a target percentage reduction in water use, denoted $\boldsymbol{y}(1)$
(*b*) a target percentage increase in the ratio of energy generated to energy consumed (in the water sector), $\boldsymbol{y}(2)$
(*c*) a target minimum mass of nitrogen-bearing materials gainfully recovered, $\boldsymbol{y}(3)$
(*d*) a target minimum mass of phosphorus-bearing materials likewise gainfully recovered, $\boldsymbol{y}(4)$.

More formally and more completely now, the influence is assessed of four promising innovations in the water sector, as candidates for attaining the target behaviours, starting from the *status quo* (and with the eventual prospect of their 100% penetration of their respective niches), as follows.

- (T1): USTs (Larsen *et al.*, 2009; Lienert and Larsen, 2007) for the production of struvite (a phosphorus- and nitrogen-based product) and ammonium sulfate (a nitrogen-based product).
- (T2): Consolidation and co-treatment of household organic (food) waste, through its conveyance in the sewerage system (consolidation of organic waste (COW)), which implies the use of food-waste grinders and the mixing of kitchen organic waste with the usual contents of household sewage, namely laundry and bathroom/toilet fluxes (Malmqvist *et al.*, 2010).
- (T3): Pyrolysis of separated sewage sludge (PSS), by which organic material is decomposed at high temperatures and in the absence of oxygen to produce gas, bioliquids and biochar (Furness *et al.*, 2000).
- (T4): Algae production in wastewater treatment facilities (AWW) (Srinath and Pillai, 1972; Sturm and Lamer, 2011) for subsequent biofuel extraction, utilising any remaining nutrients in treatment plant effluent flows, for example, in the event AWW is implemented jointly with UST.

Innovations (T1) through (T4) are incorporated into the model $\boldsymbol{M}$ by way of parameters that are elements of the overall parameter vector $\boldsymbol{\alpha}$. While they are all water-sector interventions, interest herein clearly lies in elucidating their implications for the energy and nutrient sectors. Conversely, the application of MSA for addressing the question of how to 're-balance the nitrogen metabolism' of Atlanta, through interventions in multiple sectors, is reported elsewhere (Villarroel Walker and Beck, 2011; Villarroel Walker *et al.*, 2012). Or, more generally, MSA is intended as a means of identifying which of the many constituent fluxes of materials–energy, in which of any of the five sectors (energy, water, food, waste-handling, forestry), might be influential or critical in attaining (future) target levels of smart metabolism or sustainability. Given the fluxes thus singled out for further attention, the search may then be directed towards identifying which technologies or unit processes might be entailed in manipulating these critical fluxes in some desirable manner. Hence the search would continue to locating the existing (or yet-to-be started) companies manufacturing and supplying the applicable existing (or yet-to-be-invented) products and services.

The purpose of this inverse analysis can now be stated succinctly as follows.

- What factors in $\boldsymbol{\alpha}$, in particular, those associated with (T1) through (T4), are found to be key in discriminating between whether $\boldsymbol{y}(1)$, and/or $\boldsymbol{y}(2)$, and/or $\boldsymbol{y}(3)$, and/or $\boldsymbol{y}(4)$ are reachable or not, in other words, what is contained within the subset of parameters $\boldsymbol{\alpha}_{\text{key}}$?
- Given these identified $\boldsymbol{\alpha}_{\text{key}}$, which of its elements, if any, are key to the reachability of *all* $\{\boldsymbol{y}(1), \boldsymbol{y}(2), \boldsymbol{y}(3), \boldsymbol{y}(4)\}$; that is, which factors in the coupled human-built–natural system encapsulated in $\boldsymbol{M}$ might be key to the potential for *none* of the target futures to be foreclosed upon, in principle?

4.1 Key technologies for smartness

The set of elements of $\boldsymbol{\alpha}_{\text{key}}$ found to be critical in some way for either the London or Atlanta case study, or both, are identified and defined in Table 1. It is apparent that they cover not only technological features, but other properties of the interactions between infrastructure and the rest of the environment (such as sewer leakage and infiltration), as well as societal features having to do with diets.

Tables 2 and 3 show how the various elements of $\boldsymbol{\alpha}_{\mathrm{key}}$ govern the reachability (or not) of the target futures $\{\boldsymbol{y}(1), \boldsymbol{y}(2), \boldsymbol{y}(3), \boldsymbol{y}(4)\}$ for Atlanta and London respectively. In fact, these futures have each been graded into progressively more ambitious target levels of resource savings and recovery, such as, for example, exceeding a 5%, then a 10% and finally a 15% reduction in water use, or recovering at least 500, then 1500, 3000 and finally 5000 t of phosphorus per annum.

Various deductions from these results are possible, of which just five are cited (briefly). First, from both Tables 2 and 3 it may be observed that reaching the targets for nitrogen and phosphorus recovery is found to be sensitive to the dietary choices of the two populations (feature F4 in Table 1). Second, there appears to be no scope for attaining the most aggressive rate of savings in water use (above 15%) in the case of London (in Table 3). Third, while the candidate innovation of algae biofuel production (AWW; feature F7 in Table 1) is identified as key in Atlanta's ambitions for increasing the 'energy independence' of its water sector (in Table 2), this is clearly not so for London (in Table 3). Interactions among the features are complex. In this instance, antagonisms are present among the degree of centralisation/decentralisation of sewerage and sewage collection, the amounts of nutrients available for recovery through the alternative UST technology and, therefore, the amounts available for supporting algae generation (AWW) when UST-directed nutrient recovery is also in place. Fourth, PSS (feature F5 in Table 1) is promising in respect of both energy and phosphorus recovery, but not at all for nitrogen recovery (Tables 2 and 3). Last, the uncertainties notwithstanding (and as reported elsewhere; Villarroel Walker *et al.* (2012)), recovery of some 12 000 t of phosphorus per annum is a reasonable expectation in the case of London (by 2050), were PSS to be installed by then at 100% market penetration.

ID	Description of system's features
F1	Water supply leakage
F2	Inflow/infiltration to sewer network
F3	Urine separating toilets (UST)[a]
F4	Diet and nutrient content in bodily waste
F5	Pyrolysis of sewage sludge (PSS)[a]
F6	Wastewater treatment (nutrient removal performance)
F7	Algae production in wastewater treatment (AWW)[a]
F8	Consolidation of organic waste (COW)[a]
F9	Water use by domestic/residential users
F10	Water use by commercial users
F11	Water use for coal-based power generation
F12	Water use for natural-gas-based power generation
F13	Direct energy use for water supply
F14	Industrial discharges to the sewer network

[a] Treated as an aggregate of two or more constituent features, such as degree of implementation, separation efficiency, and process operating conditions.

Table 1. Key constituent technologies and features of the multi-sectoral metabolisms (of both Atlanta and London) for reducing water use, improving the energy ratio and nutrient recovery

To summarise, it is possible from this kind of analysis to appreciate on which innovations (within $\boldsymbol{\alpha}_{\mathrm{key}}$) the attainability of which target-performance goal(s) (the various $\boldsymbol{y}$) might crucially hinge. Facets of the economic feasibility implied in reaching these goals will now be examined.

4.2 Fairness: who pays, who gains

Estimates of the potential financial returns attaching to the reachability of the performance aspirations in Tables 2 and 3 are summarised in Table 4. Before proceeding, however, it is necessary to note the limitations of these estimates. First, they are monetary sums relating to only the operational phase of technologies within the city's infrastructure, not to either what precedes or follows that stage in a project's life cycle. In other words, and most significantly, they do not take into account the costs of capital works required to reconfigure the city's infrastructure in order to implement any of the candidate technologies (T1) through (T4). Second, these estimates are not net present values; they have not been discounted over time. Third, the cost savings associated with water-use reduction are savings accruing, in principle, either to the water utility (in supplying the water) or to the domestic or commercial consumers of the water supplied. Any such savings possibly associated with the operations of those companies using water in generating power are entirely absent from Table 4. It is noted in passing, however, that water use for natural-gas-based power generation (factor F12 in Table 1) has been identified as key to attaining the various target reductions in overall water use in both Atlanta and London (Tables 2 and 3). Last, the estimates of Table 4 take no account of the (presumably beneficial) financial implications of local, within-city nitrogen- and phosphorus-based resource recoveries replacing equivalent (imported) masses respectively of their non-local, first-manufacture and first-extraction elsewhere.

A salient feature of Table 4, then, is the ranking of the magnitudes of the monetary values associated with attaining the various resource conservation and recovery targets. The cost savings for water-use reduction (target $\boldsymbol{y}(1)$) are roughly an order of magnitude greater than the financial benefits

							Nutrient recovery per annum: t × 10^3							
Water use reduction: %			Energy ratio increase: %				Nitrogen				Phosphorus			
5	10	15	20	50	100	150	2	4	8	12	0·5	1·5	3·0	5·0
F1	F1		F2	F2	F2	F2	F2		F2		F3	F3	F3	
F3	F3		F3		F3		F3	F3	F3	F3		F4	F4	F4
F9	F9	F9	F5	F5	F5	F5		F4	F4	F4	F5	F5	F5	F5
F10	F10		F6	F6	F6	F6						F6		
F11	F11	F11	F7	F7	F7	F7								F7
		F12	F13	F13	F13	F13							F8	
				F14		F14								

Note: see Table 1 for explanation of F1 to F14.

Table 2. Summary of RSA results associated with Atlanta showing key features for achieving a set of suggested targets

attaching to the nutrient recovery targets (***y***(3) and ***y***(4)), which in turn are approximately another order of magnitude greater than the rewards from energy savings/production (in the water sector) (***y***(2)).

It is, of course, one thing to generate foresight regarding estimates of benefits (and costs) on a broadly undifferentiated and societally detached system-wide basis (as in Table 4), covering multiple sectors, utilities and stakeholders, each with their quite different and frequently strongly opposed aspirations. It is quite another to reveal who might bear the future cost and who might reap the future rewards (and by how much) of making the transformation to a smarter urban metabolism. What lies below the headline numbers of Table 4 must be examined in somewhat greater detail.

Thus, it is now assumed that all the benefits of attaining the target savings in water use (***y***(1)) are those of the consumers of the water, not the utility/enterprise supplying the water. If, therefore, a household of three individuals in London were able to reduce its water consumption by 10%, it would save some US $24 annually. The same relative percentage saving in Atlanta would be worth about US $57 each year (on an identical unit cost basis), because of its currently larger per capita consumption of water. But at least millions of individual stakeholders are benefitting and on an equal, fair, basis.

On the downside of the city, there are just three centralised wastewater treatment plants in London where the three performance targets for energy, nitrogen and phosphorus recovery can be beneficially improved. It would seem that all

							Nutrient recovery per annum: t × 10^3							
Water use reduction: %			Energy ratio increase: %				Nitrogen				Phosphorus			
5	10	15	20	50	100	150	2	4	8	12	0·5	1·5	3·0	5·0
F1		—	F2	F2		F2	F2	F2		F2	F2		F2	F2
F3	F3				F3		F3	F3	F3	F3	F3	F3	F3	
F9	F9		F5	F5	F5	F5		F4	F4	F4			F4	
F12	F12		F6	F6	F6	F6	F5				F5	F5	F5	F5
			F8	F8	F8	F8				F6			F6	
				F9							F7			
			F13	F13	F13	F13								F8

Note: see Table 1 for explanation of F1 to F14.

Table 3. Summary of RSA results associated with London showing key features for achieving a set of suggested targets

Water use reduction: %			Energy ratio increase: %				Nutrient recovery per annum: $t \times 10^3$							
							Nitrogen				Phosphorus			
5	10	15	20	50	100	150	2	4	8	12	0·5	1·5	3·0	5·0
50	101	151	0·4	1·1	2·1	3·2	2·5	5·0	10·1	15·1	1·7	5·2	10·3	17·2
32	64	—	1·2	2·9	5·8	8·7								

Values considered the following information: US farm prices per ton for urea fertiliser (46% N) and super phosphate (46% PO_4) are about US $526 and $633 respectively (data from USDA); electricity price for industrial users is 6·8 cents per kWh (data from EIA); average US residential water cost of $1 per cubic metre (averaged data from www.circleofblue.org), assuming an industrial water rate is 30% less than the public supply water rate; energy benefits estimated as average total savings in the electricity bill.

Table 4. Potential annual economic benefits of each performance aspiration in millions of US dollars. Figures in the second row are for London, when these differ from those of Atlanta – the water and energy targets are relative (percentage) changes, hence a function of differing initial (base-case) conditions for the two metropolitan areas

the resulting profits and benefits should rightfully accrue to the water/wastewater utility/operator.

Spun this way – of who saves, who gains (and who pays) – the great divide in the rough, preliminary estimates of Table 4 is between millions of water consumers, on the one hand (through $\boldsymbol{y}(1)$), and the (single) wastewater utility, on the other (through $\boldsymbol{y}(2)$, $\boldsymbol{y}(3)$, $\boldsymbol{y}(4)$). But is this fair or rightful? For while the utilities for London and Atlanta ought to be rewarded for recovering the nitrogen and phosphorus resources, it is each and every one of us who buys the food that results in the nitrogen and phosphorus being there to be recovered. Does this imply some kind of ownership thereof in their subsequent, downstream recovery? For that was how it was expressed (in effect) by an entrepreneurial member of a community in peri-urban Accra faced with the prospect of ecosan, resource-recovering toilets being introduced (Kwame, 2007; see also, Beck, 2011). Would composting his residuals (and those of others) be a waste of his time, he asked, in the absence of their having a decent re-sale value (Kwame, 2007)?

While acknowledging the preliminary nature of these numerical analyses and results, it is possible to begin to discern the magnitudes of the incentives – and to whom they relate – for making any change towards a smarter urban metabolism. The point, moreover, is this. To be able to have such foresight about the *future* distribution of costs and benefits amongst these several stakeholders (water utility, power generators, other industries/commerce, and householders), would surely have a bearing on how they would *today* negotiate with each other in building (or dismantling) the social legitimacy of the policy and technology options necessary for making any change towards realising the various target-performance ambitions of Tables 2 to 4 (Beck *et al.*, 2011). Such computer-generated foresight, of course, is a significant novelty, relative to the historical analyses of Geels (2005, 2006). He enquired into the nature of the push–pull forces of the broad socio-technological transitions whereby sewer systems came to replace cesspools in the Netherlands over the period 1840–1930 and, likewise, piped water supply achieved predominance there between 1850 and 1930. How might the change now self-consciously sought – from viewing nutrients-as-pollutants to nutrients-as-resources (Beck *et al.*, 2012) – be influenced (or not) by society's access to computer-generated foresight? The question is both interesting and important, but beyond the scope of the present paper.

5. For society: privileged non-foreclosing interventions

As argued elsewhere (Beck, 2011; Gyawali, 2004; Thompson, 2011a), the distinction between the distant, inter-generational future and the present may be vital for securing sufficient, if not complete, buy-in to what can be done 'tomorrow': to take an immediate, first, practical step towards the change we seek, knowing full well that several successive steps, in fact, many (most probably), will be required to attain the target behaviour.

Who pays, who gains in the process, are contentious matters. Even the embedded choice of an inter-generational discount rate in the *Stern Review on the Economics of Climate Change* (Stern, 2006) has been hotly debated and, moreover, among economists of broadly just one of the several (opposing) schools of economic thought (Godard, 2008; see also Beck, 2011). Sustainability is itself an essentially contested concept (Thompson, 2011b). These are vexed enough issues, yet they surely do not exhaust the repertoire of grounds for dispute and disagreement.

Indeed, 'they will never agree', said the nineteenth century wit, the Reverend Sidney Smith, when he saw two women shouting at each other from houses on opposite sides of an Edinburgh street, 'they are arguing from different premises'. Theorists of plural rationality (e.g. Adams, 1995; Douglas and Wildavsky, 1982), not to mention theorists of decision making under contradictory certainties (Thompson, 1985), like to use this story as a way of getting to grips with the 'messiness' that characterises so many policy debates, as doubtless will be the case here in migrating towards smarter forms of urban metabolism. The different premises in these debates concern human and physical nature. People view the man–environment relationship in profoundly differing ways (Thompson, 2002). The theory maps these mutually opposing perspectives in terms of four forms of social solidarity: four ways of organising, each of which is, at the same time, a way of disorganising the other three (Thompson, 2008; Thompson *et al.*, 1990).

There is neither space nor need to elaborate further upon the theory and its relevance for developing forms of governance for enabling (or disabling) the kinds of technological and policy innovations that might be entailed in attaining a smarter urban metabolism. The authors' arguments are set out in full in Beck *et al.* (2011) and Beck (2011) (see also Beck *et al.*, 2012). Suffice it to say, the four social solidarities can be labelled as those of the individualists (I), the hierarchists (H), the egalitarians (E) and the fatalists (F), among which, I and H should be easily recognisable as roughly the solidarities of those who believe respectively in the supremacy of markets and regulations. The authors fully expect each to come to the table of the debate more than ready to express their aspirations (greatest hopes; worst fears) for the distant, inter-generational future of their cherished city system, namely, respectively *their* target outcomes, or $\boldsymbol{y}(H)$, $\boldsymbol{y}(I)$, and $\boldsymbol{y}(E)$ (or plural behaviours, B_i, for $i = 1, 2, 3$). In theory, there is just this threesome, since the fatalist solidarity, by definition, is supposed to be not sufficiently motivated to come to the table of the debate in the first place. The authors further acknowledge that $\boldsymbol{y}(H)$, $\boldsymbol{y}(I)$ and $\boldsymbol{y}(E)$ will inherently be subject to gross uncertainty. In practice, it is noted that it is not at all straightforward either to elicit such stakeholder aspirations (Fath and Beck, 2005) or to translate them into the numbers required by a computer model (Osidele and Beck, 2003).

In addition, the possibility is allowed of H, I and E holding to their own respective convictions about the physical and economic knowledge bases undergirding the relationships encoded within the MFA model ($\boldsymbol{M}$) of the MSA, as did van Asselt and Rotmans (1996) in their earlier, related work on uncertainty, climate science and the formation of policy for combating climate change. In other words, there can be an $\boldsymbol{\alpha}(H)$, $\boldsymbol{\alpha}(I)$ and $\boldsymbol{\alpha}(E)$ determining how the plural $\boldsymbol{y}(H)$, $\boldsymbol{y}(I)$ and $\boldsymbol{y}(E)$ might be attained. In general, this allows for exploration of the reachability of one solidarity's aspirations, say $\boldsymbol{y}(I)$, given the presumption of another's convictions, their science, their economics and their technology preferences all being granted (perfect) validity instead, as in $\boldsymbol{\alpha}(E)$, for instance (see van Asselt and Rotmans, 1996).

Bringing together the two products of the inverse analysis – the reachability assessments (and their plausibilities) and the $\boldsymbol{\alpha}_{\text{key}}$ – it may be of very special and deep interest to the negotiating parties to apprehend whether there are any elements within $\boldsymbol{\alpha}_{\text{key}}$ that appear to be key in *not foreclosing* on the reachability of any of *their* own plural futures $\{\boldsymbol{y}(H), \boldsymbol{y}(I), \boldsymbol{y}(E)\}$. Thus, while one solidarity, say the egalitarians (E), might be obdurately opposed to a policy pandering to the aspirations of the hierarchists (H), to embark immediately (tomorrow) on a path to attaining the distant, inter-generational $\boldsymbol{y}(H)$, this snubbed (E) solidarity is not yet obliged to abandon what it cherishes for that long-term future. For this would be what lies at the core of their convictions about the way the world is: the abiding and reasonable prospect of some day attaining $\boldsymbol{y}(E)$ instead.

Looking back to Tables 2 and 3, therefore, something now of very special significance can be identified: UST (feature F3 from Table 1) is the single innovation consistently of critical significance across all the savings/recovery targets: for saving water, increasing the energy production/consumption ratio, and recovering nitrogen and phosphorus nutrients. But there, in Section 4, the computational analysis of MSA was addressed to the task of identifying what features of the model are found to be key to the reachability of multiple, expert-advocated resource-recovery targets (written by the authors), that is, the 'abstract' future behaviours $\{\boldsymbol{y}(1), \boldsymbol{y}(2), \boldsymbol{y}(3), \boldsymbol{y}(4)\}$. Here, suppose that a similar result were to be obtained for an MSA directed at the community-authored (and passionately held) aspirations for *their* plural futures $\{\boldsymbol{y}(H), \boldsymbol{y}(I), \boldsymbol{y}(E)\}$. Put this way around, in other words, in a much less detached, much more socially constructed context, UST would extend the promise of *not* foreclosing upon any of the (imagined) community–societal aspirations for the future. It would be the one feature all solidarities – upholders of each of the plural moral positions on the man–environment relationship – might have a strong interest in adopting in order to change the material flows coursing around and through the metabolisms of both London and Atlanta; and it happens to be a technological innovation. In fact, it is a very small, highly local and personal innovation, with yet literally global ramifications for material fluxes, quite in line with the scope of earth systems engineering. It might be called a 'privileged, non-foreclosing' candidate innovation. A start could be made in implementing it today, while justifiably noting, with due social legitimacy, that it is capable, in principle, of yet realising any one of society's plural, multiple aspirations generations hence.

The change to using USTs, it is observed, could also be just what might be needed to save both water and money (albeit modestly) within individual households and to yield the beneficial gains in energy, nitrogen and phosphorus recovery, so that – just as advocated – nutrients would by then be viewed as resources, not pollutants. Would introduction of the UST be perceived, therefore, as a 'win–win' financial opportunity, at least for both householders and the water/wastewater utility, or (better still) as a win–win–win (or not-lose–not-lose–not-lose) proposition for the contending ways in which members of the *I*, *H* and *E* solidarities view the man–environment relationship?

6. Conclusions

If engineering sustainability is understood as a school of thought and body of methods leading to engineering or technological innovations that are environmentally benign, economically feasible and socially legitimate, this might almost be too good to be true. That notwithstanding, a computational approach – MSA – has been introduced herein which is capable of revealing such possibilities and acting as one strand of support in systems of city governance as cities seek to re-configure their material–energy metabolisms in smarter, climate-repairing ways (see also Fink, 2012). In particular, it has been argued that costs might not be the only monetary facet of those components of infrastructure, such as the management of wastewater, that are traditionally conceived of as sectors where policy is driven by pollution control alone. There are profits to be had from resource recovery. Drawing upon the ideas of adaptive community learning (set out fully elsewhere; Beck (2011) and Beck *et al.* (2002)), it has also been conjectured that some specific technologies and forms of re-engineering might be privileged, non-foreclosing interventions, hence likely to attract greater (as opposed to less) social legitimacy. In other words, these interventions might have a greater likelihood of being implemented 'today', as a first step towards the more distant inter-generational aspiration of cities with smarter metabolisms.

Inevitably, any such analysis has its limitations. In respect of elevating the environmental benignity of the city's metabolism, the present paper has considered candidate technological innovations in the water sector alone, when clearly there are innovations across multiple sectors that are worthy of assessment through the proposed MSA. In addition, understanding much better the capital works costs of infrastructure re-configurations, in particular those of the water sector, will be needed before arguments regarding economic feasibility can be fully addressed. Last, when it comes to matters of social legitimacy, it is not conjecturing around the results from computational foresight that may be key, but what structures of governance (albeit with high deliberative quality) can be realised in practice (Beck *et al.*, 2011; Gyawali, 2004; NWCF, 2009).

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