Synergy in the City: making the sum of the parts more than the whole

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Abstract Infrastructure provides the life-blood of our cities, enabling us to congregate in large numbers – it delivers our needs and wants, and removes our wastes.

The pressures on existing infrastructures are significant: demand is beginning to outstrip supply; aging infrastructure poorly maintained presents an increasing risk; and rejection of urban sprawl forces increasing population density. At the same time, the drivers for infrastructure are changing. We are beginning to recognise ecological limits to supply, leading to shifting expectations, for example, from 'remove waste' to 'recapture nutrients'. We now know that a sustainable future requires step changes in material use intensity, which has further infrastructure implications. We have witnessed it already in communications. For water and energy, and therefore, for transport also, the step changes are on the horizon. Community expectations are moving too, for example, from separating home and work towards co-locating them.

In this paper, we explore three responses to these pressures and opportunities. Firstly, we look to ecosystems for principles of sustainable infrastructure. Efficient and effective communication, material and energy flows, and waste removal are also the key to well-functioning ecosystems. We explore what the ecosystem concepts of 'integrity' and 'health' mean when translated into the context of sustainable urban infrastructure. We explain how 'integrity' translates to 'visibility', and 'health' translates to 'resilience', and explore what these might mean in practice. Secondly, we look to the increasingly networked, interlinked nature of cities for opportunities to recognise and design in 'infrastructure leapfrogs': step-change enabling synergies between water, stormwater, wastewater, waste, energy, transport, and communications infrastructures. Finally, we consider tools that will help us identify when and how to act. By definition, forecasting cannot help to identify or plan for the step changes required to respond to all these pressures, since forecasting confines us to incremental change within the boundaries that we know. The combination of backcasting and integrated resource planning might help. Backcasting enables the identification of the kinds of step changes required. Integrated resource planning, incorporating least cost planning, informs the choice and timing of the step changes. It enables logically consistent comparative economic analysis of alternatives because it focuses on meeting the service provided, rather than providing a unit of supply. Together, these three responses could enable city infrastructure to become more than the sum of its parts.

Keywords Systems planning, sustainability, infrastructure, backcasting, water, energy, transport, urban design, integrated resource planning, least cost planning.

Urban infrastructure at the crossroads

Physical infrastructure is a necessity for all stationary communities – it is in part what enables us to move away from a nomadic existence and begin to congregate in ever-increasing numbers. Roman aqueducts are part of the much famed early generations of infrastructure, mobile telephones have revolutionized the here and now, and the future is guided by our imagination. Over decades and centuries, the complex network of urban water, energy, transport, and communications infrastructure has evolved and expanded. Now, however, we are at a crossroads. The pressures on existing infrastructure are significant and mounting, and the objectives we want our infrastructure to meet are changing radically.

Infrastructure faces significant pressures

The pressures on urban infrastructure planners are many-fold. The responses are also diverse.

Firstly, existing highly centralised systems are reaching their limits[1] in terms of meeting current demands. Meanwhile, demand for the services supplied by these infrastructures continues to increase as populations[2] and economies grow. Responding to this pressure provides an opportunity to both manage demand down as well as identify alternative supplies (see Mitchell *et al*., 2004a).

Secondly, these same infrastructures are, at best, being inadequately maintained (see, for example, Engineers Australia's national infrastructure report card (IEAust, 2001) and, at worst, approaching the end of their useful life (e.g. Sydney Water Corporation's recent tender for retrofitting water mains (SWC, 2004)). We are just beginning to realise the massive looming cost of maintaining and replacing our buried infrastructure. For water and wastewater infrastructure replacement in the USA, some estimates put the cost at USD$1 trillion over the next 20 years (AWWA, 2001, p17). In addition, expenditure on repairs is expected to triple because aging pipes are more prone to breakage[3]. Responding to this pressure presents an opportunity to rethink the highly centralised nature of current infrastructure, and to consider investing locally. For water, this means co-locating sources and end uses, investing in distributed generation and treatment, rather than transport; for energy, investing in distributed generation, rather than centralised generation and distribution; and for transport, investing in access rather than mobility (Berry *et al*., 2004).

Thirdly, we see increasing rejection of urban sprawl. Over just twenty years (1972 to 1992), with independent travel made possible by the private car, Sydney has grown in area so much that the change is recognisable from space (CSIRO, 1998). Melbourne has also spread in most directions but there the policy response has been earlier and stronger, with Melbourne 2030 embodying Australia's first urban growth boundary; a planning-based regulation limiting the area of land available for the city. More people and less land available means either densities in cities must increase or people must be encouraged to settle in rural and regional areas; both are likely. Responding to the pressures of increasing urbanisation and density provides new opportunities to implement step changes towards a qualitatively more effective kind of service provision.

Finally, and perhaps most significantly, we see changes in the objectives that infrastructure is being asked to meet. We expand on this below.

Infrastructure objectives are changing

There are two elements to the changes in infrastructure objectives: changes in our understanding of limits to resource availability, and changing community expectations.

The notion of limits to resource availability gained prominence with the publication in 1972 of 'The Limits to Growth' (Meadows *et al.*). We know that a sustainable future for the all the world's population is predicated on significant step changes in material use intensity, perhaps as much as tenfold reductions (Schmidt-Bleek, 1997) or even higher.

Increasing recognition of limits to resource availability is behind two significant shifts in the water industry. These shifts are in their infancy now, and promise to be significant drivers in the short, medium, and long term. The first is the move from commodity supply to service provision[4] (Mitchell and White, 2003), from a focus on 'providing more' (supply side thinking) to 'using efficiently and appropriately' (demand side thinking). A second shift is from a focus on 'removing waste' to 'recapturing nutrients'[5].

Changing community expectations represent challenges of a different kind. We used to prefer to separate industrial and manufacturing areas from residential areas. Changes in workforce demographics and massive

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[1] For example potable water supplies in Sydney, Perth and Gold Coast; energy supplies to Sydney's CBD; and road transport corridors in South East Queensland and Melbourne

[2] Through the combination of around 1,000 new residents each week and decreasing average house size, DIPNR expects 500,000 new homes in the greater Sydney Region over the next 25 years (DIPNR 2004 p6)

[3] Some have argued that these are over-estimates, and that improved asset management (e.g. risk-cost approaches) will lead to more effective targeting of investment. Our view is that asset management will provide some relief, however, the size of the problem will be largely unchanged.

[4] The move to a service economy has already underpinned major change in other sectors. For example, in manufacturing, the conceptual move to providing a service rather than a product has enabled business expansion at the same time as drastic reductions in waste production and extended product longevity (Professor Dexter Dunphy, ABC Radio, 28 April 2002, Transcript available on-line at http://www.abc.net.au/rn/bigidea/stories/s519567.htmand). In the energy and water industry, sub-contracting specific services to manage demand is a significant growth area (Berry et al, 2004, p29)

[5] Global phosphorus deposits are expected to deplete in the next 50 - 80 years (Birch 1976). The mass of phosphorus that leaves Sydney's sewage treatment plants each year is said to be roughly equivalent to the mass of phosphorus used annually in broad acre cropping in NSW, and therefore represents a significant potential resource.

improvements in pollution prevention mean that preference has little standing now. Instead, we are turning to mixed use developments, co-locating work and home, changing the need for transport. In keeping with this, we see movement away from highly stratified cities towards high diversity on a local scale: from maximising transport towards centres of exchange to maximising equitable access towards distributed opportunities for exchange.

Conceptual models and tools help choose between paths

Resource limits and community expectations overlaid on the complex, highly constrained, urban system will result in emergent behaviour. Batten explores emergent behaviour as a property of cities (Batten *et al.* 2000), and notes some collective properties of urban systems can be predicted from our knowledge of individual sub-systems but some (or many) collective properties cannot be predicted (p 58).

Responding to these pressures and changing objectives provides significant drivers for systematically rethinking our urban infrastructure, and specifically, for the water industry to change its direction. Firstly, we can begin to design and implement and evaluate qualitatively different systems, e.g. in terms of technology scale and management models. Secondly, there is the search for new synergies between elements of the water cycle and between the water cycle and other infrastructures. Thirdly, we can look for ‘leapfrog’ technologies – the mobile telephone equivalents for other infrastructures e.g. avoiding water as a catch-all solvent, or avoiding heat as the source of electrical energy.

By definition, step changes and emergent properties such as these are difficult to forecast: so we need different approaches. In the sections that follow we explore three responses. Firstly, we seek insights from relevant conceptual models of comparably complex systems (ecosystems). Secondly, we look for examples of design and technologies that could hold the key to unlocking leapfrog synergies within and between infrastructures. Thirdly, we review two tools that help us identify where (backcasting) and when (least cost planning) to act.

Learning from nature

Ecosystems may present a useful conceptual model to gain insights into city infrastructure. Ecosystems are diverse groups of flora and fauna with complex relationships and stringent requirements. Efficient and effective communication, and intricate material, energy and waste flows, are key to both well-functioning ecosystems and cities. Ecosystems can be characterised by ‘health’ and ‘integrity’: James Karr argues that these are qualitatively different concepts, and that both are necessary for ecosystems to function well (Karr 1996). These are foreign concepts for infrastructure, so here we translate them to identify key characteristics for well-functioning city infrastructure. According to the Macquarie Dictionary:

Health/ well being, vitality, resilience
Integrity/ 1. honesty 2. state of being entire, whole, undiminished

What might ‘health’ translate to for a city’s infrastructure?

- Adaptive, resilient systems
- No degradation of the serviced site and areas beyond the site
- Liveable, equitable, vital communities

So, as the objectives for infrastructure change radically to reflect our new understandings of resource availability limits and community expectations, eg from ‘remove waste’ to ‘recapture nutrients’, resilience is a key characteristic: flourishing despite changing inputs and expectations.

What might ‘integrity’ translate to for a city’s infrastructure? Perhaps making visible the infrastructure that supports us; making visible our reliance and our impact on the natural environment. Enabling the city to be seen and experienced as a connected, integrated system of inputs and outputs.

So, infrastructure that is well functioning, that meets our changing needs and enables progress towards sustainability might demonstrate resilience and visibility. Each concept warrants further exploration and explanation.

The benefits of resilience

An infrastructure system with ‘resilience’ is one that can respond to the kinds of technological shifts and pressures common in the twenty-first century. Resilience implies vitality and flexibility, an ability to adapt and change. It contrasts starkly with ‘lock-in’: a gradual ‘carving out’ of a particular (infrastructure) path (Batten *et al*, 2000).

Centralised infrastructure is associated with perceived ‘lock-in’. One contributing factor is conventional cost estimation processes that focus on the incremental addition to a centralised system, resulting in underestimates of the total system costs to provide the extended capacity. For example, in water services, ‘head works charges’ incorporate the costs of the added load from additional connections on supply and treatment systems. A resilient approach would use a process like least cost planning[6], that compared whole systems and included all the costs associated with supplying the services through various means.

Resilient infrastructure would be modular, enabling rapid uptake of technological improvements, and more closely matching demand with capacity to supply, thereby maximising the performance of both the infrastructure itself and the capital invested in it. Meeting the demands of increasing population densities through infill and brownfield developments requires retrofits of existing urban infrastructure. The choice is between marginal additions to centralised infrastructure, or using the opportunity to begin to make step changes to more resilient systems.

There is an intriguing relationship between resilience and risk. Here, we consider three related issues: calculating risks, financial risk, and security risk.

Risks are generally assessed as the product of the probability of a particular failure and its consequences (see for example Australian Standard 4360:1999). Highly centralised infrastructure may tend towards lower probability of failure, because of organisational drivers and asset management responses. However, the consequences of failure are high simply because of the degree of concentration. So, when a failure occurs in a centralised system, the consequences can be significant for the environment and/or public health because, for example, the number of people affected, or the volume of wastewater inadequately treated, is large. Distributed systems, on the other hand, may tend towards higher failure rates (at least whilst more effective management models are developed and implemented), but have relatively low consequences. For example, a water treatment ‘failure’ in 1998 resulted in Sydney Water advising its 4 million or so customers to boil their water prior to use. A water quality problem in a household raintank affects only the handful of people using that supply. Thus, distributed systems may be more resilient.

Security has emerged as an increasing concern for key infrastructures in our post- September 11 world. Twenty years ago, Brian Martin (1984) argued that decreasing society’s physical vulnerability was a key strategy for non-violent conflict resolution. He argued that highly centralised utilities (including dams and power stations) provide an obvious weak point open to attack. Designing weak points out of the urban system through reducing resource use and implementing decentralised treatment reduces this risk, and is consistent with distributed, resilient systems.

Finally, in a study of wide-ranging mega-infrastructure projects, Flyvberg (Flyvbjerg *et al*, 2001) showed how the irreversibility of investment decisions (connected in part to ‘lock-in’ and in part to sunk costs incurred through project commencement) and the scale of investment (which on mega-projects can impact on a country or region’s economic development) mean both the likelihood and consequence of risks are high. To avoid or reduce these risks, they identify institutional change as crucial, noting the following four recommendations:

- ☐ Performance specification rather than concept design by public authorities;
- ☐ Requiring formal risk capital;
- ☐ Increased transparency in decision making;
- ☐ A clear regulatory regime and policy context; and

These recommendations are consistent with the concepts of resilience (meeting the need) and visibility (integrity). This brings us to a discussion on visibility.

Visibility

We see visibility as a two-way relationship between people and infrastructure. Firstly, infrastructures need to respond to people’s needs for services (as opposed to resources), and secondly, people need clear signals and information about their resource use in order to be able to make decisions and change behaviours.

Just as Flyvbjerg *et al.* (2001) argue for performance specification to overcome the limitations of deterministic concept design, we argue that a service focus moves us away from optimising the flow of litres of water, electrons or motor vehicles. Instead this perspective increases our understanding at a basic level of the service to people—their needs—so we can optimise the resources to meet the needs. At the heart of this approach is a clear understanding of the interaction between the natural resource and people, for example the services delivered to citizens who use water are hot showers and clean clothes. For the latter at least, water is not the only resource capable of delivering this service.

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[6] See Fane et al, 2003 for a discussion of least cost planning analysis to compare supply and demand side options.

Finite resources moderate this service potential and so necessitate the other side of the two-way exchange: people responding to natural resource signals. Graham and Marvin (2001) describe cities as a “perpetual flux of infrastructurally mediated flow, movement and exchange” (p.8). They say urban infrastructure, including water treatment systems, streets and transport, telecommunication and energy grids are “mediators between nature, culture and the production of the city” (ibid). This very mediation, long a symbol of order and progress, now offers a means to engage people, linking them with their natural environment and increasing our understanding of the nutrients feeding the lifeblood of cities.

Engaged communities where people can make informed decisions about resource use require the pre-cursor of relationships between people and the resources they use. The current well-intentioned form of ‘mediation’ of people’s interaction with resources via largely invisible infrastructures dis-empowers us, reducing both our understanding of the relationship between our actions and resource consumption; and our ability to reduce resource use should we choose to. Other solutions are possible, and visibility could be a key.

Our understanding of how learning happens, and thus how change is enabled, points to the need for visibility of the infrastructure that supports our urban ecosystem. In his seminal book on communities of practice, Etienne Wenger (p229, 1998) explains how learning cannot be designed: it belongs to the realm of practice and experience. Second generation knowledge management (Philips *et al.*, 2004) recognises the need for personal engagement too – it takes a demand-side approach, and focuses on knowledge production by learners on the job. Finally, Donella Meadows (1998) explains “people can’t respond to information they don’t have. They can’t react effectively to information that is inadequate. They can’t achieve goals or targets of which they are not aware. They cannot work towards sustainable development if they have no clear, timely, accurate, visible indicators of sustainable development” (p5). The kind of step changes we envisage will involve radically different infrastructures and will need citizens thus engaged with their cities. What follows is our foray into the future of urban infrastructure.

Critically linked urban infrastructures

Dupay (1991) identifies the networked character of modern urbanism as its single dominant characteristic.

These seemingly distinct urban infrastructure systems (water, energy, transport, communications) are actually dependent systems that rely on each other, and have co-evolved over time, driven by policy, governance and business structures, people’s expectations, and changing notions of the environment.

Infrastructure linkages are increasingly apparent and some links provide synergistic opportunities. A simple example is that three per cent of energy usage in the US is for water treatment, supply and wastewater treatment and this doubles if you include the energy used in homes to heat the water (Cohen *et al*, 2004). This means saving water saves energy. It is exactly this ‘synergy in the city’ that we are searching for.

We propose that backcasting and least cost planning across the infrastructure in cities, at a range of scales, applying the criteria of resilience and visibility, will let us ‘tunnel through the cost barriers’ (Lovins *et al.*, 2002), minimise resource use, tap synergies and provide better service at lower cost. Far from being a utopian dream, existing processes are already moving in this new direction. In this section, we explore potential contenders for energy and water.

Infrastructure leapfrogs: the mobile phones of water and energy

Resource constraints and community expectations mean we need ‘leapfrogs’ or step changes in resource use and servicing. Resource conservation will be an essential component, and step changes in technology are also needed to meet the kinds of objectives communities are setting for themselves.

As an incredibly abundant molecule, water has been our universal solvent for millennia, and our universal conveyor for centuries. It is in these uses that the leapfrog is most likely to appear. For example, as a solvent, supercritical[7] carbon dioxide holds intriguing potential.

It is in wide use now as an industrial solvent for processes as diverse as decaffeination in coffee and complex pharmaceutical production. In an intriguing advance, an Australian design about to be paraded at an international design event[8] uses supercritical CO_2 as the solvent in a new dishwasher.

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[7] A supercritical fluid is defined as a substance above its critical temperature and pressure. For CO_2, this is above $31^{o}C$ and around 72 atmospheres. Supercritical fluids exhibit properties of both gases and liquids: like gases, they expand to fill any container, and like liquids, they dissolve materials.

[8] The Buzz, ABC Radio National, 9 Oct 2004

As well as avoiding water use, the design is surprisingly energy efficient. Increasing the pressure of CO_2 from atmospheric to supercritical takes only twice as much energy per unit mass as increasing the temperature of water from 15°C to 60°C. In addition, very little CO_2 may be needed, firstly because supercritical fluids have incredible diffusivity, essentially no surface tension, and terrific solvation potential, and, secondly, because it is recyclable - dropping the pressure slightly changes the CO_2's properties (i.e. the supercritical gas reverts to a liquid) and the dishes' contaminants drop out of solution in a highly concentrated form. The CO_2 would be readily separated and collected, and only a little energy would be needed for the marginal increase in pressure to take it back to the supercritical phase for reuse.

In energy, disappearing fossil fuel sources along with carbon taxes and trading permits are just some of the influences encouraging us to discard cumbersome, inefficient generation processes. Fossil heat and multiple mechanical transformations and massive distribution losses will be superseded by direct (bio)chemical energy transformations. Fuel cells hold great potential here (eg Lovins *et al*., 2002) and glimpses of other technologies are increasingly prevalent.

Hydrogen is the primary input to run fuel cells. The hydrogen economy prospect has not yet overcome the critical issue of a sustainable energy source to make the hydrogen. At present, fuel cells rely mostly on natural gas; essentially a transition fuel in terms of sustainable energy[9]. Biological production of hydrogen could hold the key: perhaps microbial fuel cells (MFCs) are the next clean energy source.

Prof Bruce Logan and his colleagues (McCann 2004) are making step changes in effectiveness in their quest to use iron-reducing bacteria with extracellular enzymes that release protons to drive fuel cell electricity production whilst metabolising waste carbon sources. Pennsylvania State University reported a major step for this technology this year when they powered a three milliwatt fan using less than a teaspoon of household wastewater—an interactive demonstration of their achievement in cutting the cost by two-thirds and increasing the electricity output by almost 600%[10].

A further leapfrog is possible through combining these two. Given the highly concentrated nature of the nutrients, this waste stream may be the perfect concentrated organics source for the microbial fuel cell. So, we could have a water free, energy efficient dishwasher using an environmentally friendly, chemically powered cleaning agent as well as distributed, high-efficiency, renewable energy production. Step changes indeed are possible, and the scale of the step changes could be significant. We need tools that will help us decide which step changes to invest in and the order of investment *i.e.* when and how to act.

A toolkit for the future

Tools are needed to structure our thinking and planning, both to take us into this brave new world of technologies we can only just imagine and to extend beyond sub-system (or single infrastructure) conceptual boundaries. This multi-infrastructure assessment is where our analysis must transition—we know this because our natural systems thrive in concert with each other and our infrastructures have co-evolved with each other and are increasingly co-dependent. We propose that some tools that might help us make the leap to this broader scale of analysis. We consider these tools next, and how they might assist engineers to make the most of their role in moving towards sustainability.

Backcasting

In searching for marginal and step change opportunities to enable resilient and visible and interconnected infrastructure, backcasting helps identify the 'what'. It has been applied in seeking to understand various ways to reduce resource use (see, for example, Dreborg 1996 and Robert *et al.*, 2002). The first step in backcasting is to describe a desired future state, most successfully done by picking a point in time that is far enough away to allow creative, innovative ideas to enter the realm of possibility and to avoid being constrained by what we know to be the current situation. A thirty-year time frame is usually workable. Given that desired future state, we then look backwards to the present, identifying alternate interim steps and sets of scenarios that will take us from the present to this desired state.

Having identified the 'what', a range of potentially useful scenarios, we need a methodology that will enable comparison between them, and help to identify which ideas to invest in, and in what order. Enter least cost planning!

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[9] Saddler et al (2004, p140) identify the long-term limits to Australian natural gas reserves

[10] See http://www.worldchanging.com/archives/000864.html or http://www.psu.edu/ur/2004/microbfuel.html

Least Cost Planning

When least cost planning is used in conjunction with backcasting (Fane *et al*., 2004), we can compare a range of ways to move in the direction of some desirable future from where we are in the present, and understand how much we as a community will pay for the journey.

Confronted with major investment decisions, increasing intensity of infrastructure and challenging multi-objectives, some sectors have turned to least cost planning. Least cost planning is an analytical approach based on a clear definition of the service provided by the resources. This shift in focus, away from volumes of water or units of electricity, raises important questions, most predominantly, 'How can we provide the same service using less resources?'. Secondary questions then arise as to how much the changes cost and where the financial burdens and benefits lie. Water service sectors are leaders in the field in terms of applying these principles in Australia and they are reaping the rewards.

The single resource conservation context in which least cost planning has been applied now has multi-objectives overlaid. Even within the water services sector the volume of water and the quality of water services to people are not the only factors in question. Environmental water quality characteristics are one of the additional parameters to maximise. Subject to locationally specific constraints, minimising sewerage effluent or flattening out peaks in demand can also be robustly targeted using least cost planning.

The opportunity exists now to extend this analysis, to ask questions like 'Where should the next 50,000 homes be located in the Sydney region if we are to deliver services to them at the lowest total long-term cost to the community?'. Least cost planning both levels the analytical playing field to allow balanced consideration of options and ensure we take the whole costs into account. We argue that least cost planning works best when we understand it as just one economic input to decision making. As we explain in the following section, evidence suggests that economic tests alone are not sufficient.

People-Environment Balance

In considering the difficult balance between the economy, people and the environment, we argue that if people and the environment are in balance then the economy can be robust but that the reverse is not necessarily true, *i.e.* a robust economy does not, by default, mean a healthy community and sustainable interactions with the environment. An example is that despite Australia's economic prosperity, a review by Fiona Stanley (Stanley cited in Gleeson, 2004) of physical and mental health indicators finds that "whilst death rates are low and life expectancy is terrific, trends in almost all other outcomes [for children] have got worse". Gleeson describes these outcomes as including birth weight, asthma, diabetes, obesity, intellectual disability, depression, anxiety, behavioural problems, drug use and child abuse. Clearly economic viability is an insufficient measurement.

An engaged populace may also demand different decision-making processes, in terms of both the locus of decision-making and the identity of the decision-makers *e.g.* citizens juries. Others (Carson *et al*., 2002) have argued that processes involving typical citizens and founded on deliberative, representative and participatory principles, may provide greater certainty for policy makers, and may help to resolve the contentious, value-laden environmental issues we face where deciding on the criteria for choosing between options is the first part of the decision making process (Mitchell *et al*., 2004b).

Concluding Remarks

Our cities have prospered because of the remarkable achievements of engineers to provide for our material needs at ever increasing densities, complexities, and delivery speeds. But the rules are changing. Our well-hidden infrastructure is facing incredible pressure: demand is outstripping supply, and its maintenance requirements are formidable. At the same time, we are beginning to recognise that there are real limits to resource availability, and our citizens are asking for qualitatively different solutions. What ought we scientists and engineers do in response?

We contend that engineers and scientists have a particular role in sustainable development: we have responsibility for devising, designing, and implementing clever ways to use the 'means' provided by natural resources to meet the 'ends' of providing services to satisfy human demands. The constraints outlined above mean that objective decisions are no longer an appropriate response. Instead, we suggest that engineers have a tremendous opportunity to be the 'honest broker' of technical and scientific knowledge (Mitchell *et al*., 2004b) in open participatory decision processes; to complement our historical strengths in forecasting with the emerging approach of backcasting; to embrace tools like least cost planning that enable us to simultaneously focus on both efficiency and effectiveness (doing the thing right and doing the right thing); to combine engineering and scientific expertise with other disciplines and understandings to achieve outcomes that cannot be conceived within a single perspective. To enact this new responsibility, we need new models for characterising the built environment infrastructure systems we create: resilience and visibility may be the keys.

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