Ascendance, Resistance, Resilience

Concepts and Analyses for Designing Energy and Water Systems in a Changing Climate

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Certificate of Original Authorship

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Abstract

This thesis synthesises a set of improved concepts and analyses for designing energy and water systems in a changing climate.

The thesis begins by reviewing the concepts that have influenced the planning, design and assessment of energy and water systems through time. The conceptual development is characterised as a series of emerging paradigms or 'waves', each providing new insights while revealing new conceptual blind spots. The review finds a series of conceptual ambiguities and tensions that may be inhibiting a more integrated perspective. Based on the premise that cities may be better characterised as coupled ecological and economic systems, the review then explores several fields seeking an interdisciplinary synthesis between ecology and economics, and finds much has been 'lost in translation' as the concepts have been adapted and operationalised.

The thesis then embarks on a broad and deep historical literature review to identify the concepts observed to underlie systemic performance in ecology and economics. In so doing, a conceptual framework is synthesised to provide a coherent model for systemic performance drawn from both disciplines. The framework comprises three attributes: the capacity of a system to thrive despite resource scarcity and competition, termed 'ascendance'; the capacity of a system to absorb variability, fluctuation and disturbance and remain essentially unchanged, termed 'resistance'; and the capacity of a system to adapt with shocks, shifts and perturbation and avoid systemic failure, termed 'resilience'. Each attribute is addressed in turn by first identifying the underlying drivers or imperatives (the 'why'), then by elaborating its various definitions within the literature (the 'what'), and then by unpacking the underlying mechanisms toward its development (the 'how').

Returning to the fields of urban water and energy planning, the thesis then explores the extent to which the conceptual framework translates and provides new insights into urban water and energy systems. The translation demonstrates a clear alignment between the conceptual findings of ecology and economics and emerging patterns in urban water and energy systems. Furthermore, the translation reveals how the conceptual framework may be applied to describe, analyse and design for improved systemic performance.

The thesis then analyses a set of candidate analytical methods for assessing each attribute of the conceptual framework, including the strengths, limitations and appropriate role of each analytical method. A set of heuristics is then developed for structuring an integrated assessment of systemic performance.

The thesis then demonstrates and validates the identified concepts and analyses by elaborating a set of hypothetical case studies supplemented by analytical modelling. The case studies provide a practical demonstration of how the concepts and analyses may be applied in a set of realistic problem situations. They further demonstrate how the concepts and analyses result in improved outcomes, both in cost-effectiveness and robustness.

A discussion of the key findings and contributions of the research follows, together with some concluding remarks regarding the research limitations and future research opportunities.

Foreword

The stimulus for this thesis was my work as a consulting researcher and policy analyst at the UTS Institute for Sustainable Futures. During my time in this role, the organisations that we worked with were grappling with a set of challenges: electricity utilities were struggling to meet their reliability standards in the face of escalating peak demand; water utilities were struggling to maintain water security in the face of a series of severe droughts experienced across Australia; and government agencies were attempting to form policies to simultaneously mitigate and adapt with the emerging reality of a changing climate.

My specific professional focus was on applying and extending 'integrated resource planning'– a system modelling, forecasting and strategic assessment approach predominantly applied in the energy and water sectors. A point of differentiation of this approach is its ability to compare a much wider range of interventions, including 'supply-side options' such as network augmentations, reservoirs and new generators, and 'demand side options' including end-use efficiency, recycling and source substitution.

However, we were increasingly finding that the concepts and analyses underpinning the approach were no longer sufficient for the challenges that we were dealing with. Faced with unprecedented demand uncertainty, electricity utilities were dramatically augmenting network capacities, leading to unprecedented rises in electricity prices. Meanwhile, water utilities across the country were resorting to the construction of a series of expensive desalination plants. In both cases the key justification for the investment was that they provided the necessary 'insurance' to maintain acceptable levels of reliability and security. Many at our institute suspected there must be a smarter way forward but the alternative responses, including embedded storage, renewable generation, and decentralised water systems, were difficult to model and assess using existing conceptual and analytical frameworks.

I suspected that economic and ecological theory might offer a more nuanced way of grappling with these challenges owing to their much deeper empirical experience with complex and adaptive systems. I therefore decided to commence a transdisciplinary PhD at the Institute for Sustainable Futures to test that theory – a journey that took me two hundred years back in time, around the world and back again, only to leave me with more questions. This thesis is the best I could do to describe what I found.

1 Introduction

1.1 The problem

The energy and water systems that sustain our cities are facing a suite of challenges that strike at their conceptual and analytical foundations.

Increasing signs of a global shift in our climate have driven calls for a rapid decarbonisation of our energy systems (IEA 2013). This transition is driving a fundamental shift in how energy is generated, distributed and consumed owing to the diffuse and variable nature of renewable energy sources. Conventional concepts of 'baseload' and 'peaking' generation are becoming increasingly limiting in the context of the rising penetration of renewable generators (Sovacool 2009) and the emergence of variable but predictable generation (Costa et al. 2008). At the same time, the conventional model of large centralised generators and radial transmission and distribution is increasingly being replaced by smaller renewable generators embedded across the distribution network (Bouffard & Kirschen 2008). The shift toward temporally variable and spatially distributed generation represent a series of challenges to energy planners, requiring a fundamental reconceptualisation of their operation and a corresponding shift in how these systems are planned and designed (Cochran et al. 2012).

Climate change is similarly driving a revolution in the way urban water systems are conceptualised, planned and designed. Water planners are increasingly being forced to abandon the assumption that historical weather observations provide an adequate reflection of future conditions (Milly et al. 2008). Faced with the prospect of potentially severe climate change, water planners have resorted to adding increasing levels of supply capacity redundancy, including so-called 'climate independent' sources such as seawater desalination. However, the limitations of conventional planning responses are driving calls for a new paradigm in the way water systems are conceptualised and planned (Fane & Patterson 2009).

Increasingly, water and energy planners are employing economic and ecological concepts such as 'diversified portfolios', 'managerial flexibility' and 'resilience' (Blackmore & Plant 2008; Wong & Brown 2009). However, there is a significant conceptual and analytical challenge remaining if planners and designers are to bridge the gap between the rhetoric and reality of these concepts. Significant ambiguity remains in the literature as to the meaning of the terms (Holling 1996; Grimm & Wissel 1997; McCann 2000; Brand & Jax 2007; Strunz 2012), a problem that has been compounded as the concepts have been applied to water and energy planning (Klein, Nicholls & Thomalla 2003; Pickett, Cadenasso & Grove 2004;

Blackmore & Plant 2008; Wang & Blackmore 2009). Furthermore, energy and water planners still lack a set of coherent analytical approaches to assess and design for those concepts, further hindering their operationalisation (Short et al. 2010).

The purpose of this thesis is therefore to synthesise a set of improved concepts and analyses for designing energy and water systems in a changing climate.

1.2 Thesis outline

The thesis begins in Chapter 2 by reviewing the concepts and analytical methods that have shaped urban water and energy planning since its formalisation in the 1950s (see Section 2.1). The conceptual development of the two fields is traced as a sequence of paradigms or 'waves', each representing the emergence of a new class of concepts and methods. The strengths and limitations of each of the conceptual and analytical paradigms are then highlighted to establish the set of challenges that motivate the thesis. Building on the hypothesis that energy and water systems may be better characterised as coupled ecological and economic systems, the review then explores several fields seeking an interdisciplinary synthesis between ecology and economics (see Section 2.2).

Chapter 3 then drills deeper into the economic and ecological literature to explore the concepts identified by the two disciplines for describing systemic performance. A broad and deep set of historical literature is reviewed, unravelled and synthesised and a consistent set of conceptual attributes and mechanisms drawn from both disciplines is identified. The resulting conceptual framework is proposed as an improved conceptual model for describing and analysing the performance of ecological and economic systems.

Chapter 4 then translates the concepts back to the urban water and energy planning context. Stepping through the attributes and mechanisms the translation identifies how the framework re-conceptualises the planning problem and highlights the key implications for urban water and energy systems design.

Working from this conceptual framework Chapter 5 then explores how the identified attributes may be practically assessed and therefore designed for. A broad set of analytical methods are reviewed and synthesised, drawing from a diverse range of disciplines including economics, environmental management, risk management, futures research, decision theory and finance. Each method is critically analysed to identify its strengths, limitations and effective role. The resulting analytical framework is proposed as a useful tool for structuring an improved assessment of urban water and energy systems.

The practical value of the conceptual and analytical frameworks is then tested in Chapter 6 using several hypothetical case studies that exemplify the concepts and methods proposed in the thesis. The case studies illustrate the potential value of the concepts and methods in realising more affordable and robust water and energy systems.

The key findings and contributions of the thesis are then discussed, followed by concluding remarks on the limitations and research opportunities arising from the thesis.

2 Paradigms: a review of the concepts shaping urban water and energy systems

The premise of this thesis is that urban water and energy systems, like any human construct, are shaped to a significant degree by the conceptual models that we bring to the process of planning and designing them (Langer 1942). This chapter therefore begins in Section 2.1 by identifying shifts in societal expectations and the impacts of those shifts on water and energy planning. The review identifies a sequence of paradigms or conceptual waves that each offer new insights while simultaneously revealing new conceptual blind spots. Taking a step back, the review highlights the conceptual tensions among the paradigms and argues the need for a more integrated and systemic conceptual model.

A central hypothesis of the thesis is that the two systems disciplines of ecology and economics offer insights that may be formed into an improved conceptual model for planning and designing urban water and energy systems. The chapter continues in Section 2.2 by identifying and reviewing ecological and economic fields that offer the best prospects for an interdisciplinary synthesis.

The chapter concludes with a critique of these fields and a statement and justification of the research questions of the thesis.

2.1 The city as a machine: reviewing the historical concepts that have influenced urban water and energy systems

The concepts and analytical methods that guide urban water and energy planning today have been shaped by a series of waves of concepts and methods or *paradigms* that have emerged in society over time. Each paradigm emerged from a growing awareness of the limitations of existing concepts and practices. Over time each paradigm then flowed on to influence urban water and energy planning through the formalisation of analytical methods. However, as will be shown below, this process has been largely organic and significant tensions remain among the concepts and methods.

This section identifies and analyses four paradigms that have emerged since the formalisation of urban water and energy planning. The review begins with the emergence of the notion of economic productivity and formal economic assessment processes in the 1950s (See Section 2.1.1). The review then traces the rise of concerns about physical scarcity and environmental degradation and their translation to environmental assessment processes (See Section 2.1.2). The inception and formalisation of risk concepts and methods is then analysed (2.1.3) together with the later emergence of the related but qualitatively different resilience paradigm (2.1.4).

The review traces the specific problem context that gave rise to each paradigm and how the concepts were subsequently adapted for use in energy and water planning as a set of formal analytical methods. Rather than focussing on the concepts and methods in detail, the section highlights the strengths and limitations of each paradigm and the tensions that remain among them. A detailed analysis and synthesis of the concepts and methods follows in subsequent chapters (see Chapters 3 and 5 respectively).

This chapter now begins by exploring the drivers that gave rise to formalised urban water and energy assessment at the turn of the 20th century.

2.1.1 Planning for economic efficiency

Though its conceptual underpinnings go much deeper (e.g. Dupuit 1844; Pigou 1920), the paradigm of economic efficiency emerged as a significant driver of our cities and societies during the post-war recovery in the early 20th century (Haber 1964; Alexander 2008).

The fundamental insight of the economic efficiency paradigm is that the resources available to a government are ultimately scarce and, as such, the assignment of resources to a specific activity is associated with a set of foregone alternative activities. Economic efficiency therefore implies assigning scarce resources to those activities that most effectively generate benefits to society.

The associated processes of cost-effectiveness and cost-benefit analysis emerged first in flood control investments in the United States. Key early milestones included the US Flood Control Act of 1936, which authorised investments 'if the benefits to whomsoever they may accrue are in excess of the estimated costs' (Prest & Turvey 1965) and the publication of the so-called 'Green Book' of proposed practices for economic analysis of river basin projects (FIRBC 1950). The analytical methods were later generalised to water and energy planning in the late 1950s and 1960s, with processes for assessing water investments (Eckstein 1958; Steiner 1959) and energy investments (Turvey 1963).

The paradigm had a significant impact on the process of urban water and energy planning. Increased attention was directed toward the economic efficiency of infrastructure investments, leading to the adoption of explicit and systematic economic assessment processes. These formal economic assessment processes drove urban water and energy planners to explicitly consider the range of strategies for achieving their goals, and their relative economic benefits and costs, indirectly driving competition and innovation.

However, the new perspective offered by the economic efficiency paradigm brought a series of blind spots into focus. For instance, while the analyses focus attention to the performance of incremental components, they typically exclude consideration of interactions with the system as a whole. The most obvious illustration of this was the limited attention paid to the physical resources that underpin urban water and energy systems. Impacts of water supply projects on aquatic ecosystems remained hidden while the depletion of fossil fuel reserves was similarly ignored. The end result was a systematic bias in assessment processes toward the depletion of natural capital (Jansson 1994), sowing the seeds of the resource scarcity paradigm.

2.1.2 Planning for physical scarcity

Although its roots stretch back at least as far back as the 19th century (e.g. Malthus 1798; Mill 1848), the paradigm of planning for physical scarcity emerged to prominence amid growing concerns of resource depletion and environmental deterioration in the 1970s (Meadows et al. 1972; Lovins 1977; Sant 1979; Guha 2000).

At its core the paradigm emphasises that sustained growth in material consumption is at odds with the finite physical resources of the planet. Efforts should therefore be made to conserve natural resources where possible through, for instance, using resources more efficiently and recycling waste.

The era gave rise to a new planning process termed ‘integrated resource planning’ or ‘least cost planning’ (Lovins 1977; Sant 1979). While urban infrastructure planners had exclusively focussed on building new infrastructure such as new generators and network augmentations, integrated resource planning suggested the benefits of exploring efficiency improvements as a viable alternative to capacity augmentations through, for instance, promoting efficient appliances.

The concepts and analyses of integrated resource planning were applied to a series of electricity planning studies in the early 1980s (Meier 1982; Meier, Wright & Rosenfeld 1983), and were later adopted operationally in the 1990s, firstly in the US (Mitchell 1992) and then internationally, albeit with mixed levels of adoption (D'Sa 2005). The concepts and methods were later adapted to water planning, once again firstly in the US (Beecher, Landers & Mann 1991), then in Australia (Howe & White 1998), and, more recently, they have been promoted internationally under the auspices of the International Water Association (Turner et al. 2007).[1]

Integrated resource planning studies brought to focus the benefits of demand management policies and programs, including consumer education programs, minimum building and appliance performance standards, rebates and other incentives for efficient resource use (D'Sa 2005).

However, despite its clear importance in justifying increased efficiency and conservation program uptake, integrated resource planning had several limitations. Critically, the approach exclusively focussed attention on the performance of individual components, thereby excluding the interactions between incremental interventions and the system as a whole. Experts have since explored the extension of the approach to account for network effects. This extended approach is termed ‘Local Integrated Resource Planning’ or ‘Distributed Resource Planning’ (Woo et al. 1994; Baughman, Siddiqi & Zarnikau 1995b, 1995a; Pupp et al. 1995; Swisher & Orans 1995; Lenssen 1996; Feinstein & Lesser 1997). However, the extended approach has not been widely adopted and has only been applied to a limited set of case studies (Orans, Woo & Horii 1994; Malik & Sumaoy 2003).

More broadly, the slow incorporation of the physical scarcity paradigm may be interpreted partly as being a consequence of underlying conceptual tensions. For instance, the economic efficiency perspective typically assumes all resources are substitutable and ignores important non-linearities and threshold effects while the physical scarcity perspective often underestimates the technical opportunities for substitution, efficiency and recirculation (Krautkraemer 2005).

This thesis argues that a deep interdisciplinary synthesis is required between the disciplines of economics and ecology to integrate the economic efficiency and physical scarcity paradigms.

2.1.3 Planning for risk

The ‘planning for risk’ paradigm arose in the engineering sector following a series of catastrophic failures in the aerospace, nuclear and chemical industries in the 1970s (Bedford & Cooke 2001).

[1] Integrated resource planning has also been adapted to solid waste planning (Markowitz 1952) and transport planning (Sundberg, Gipperth & Wene 1994).

At the core of the new paradigm was the recognition that although the future is impossible to predict with certainty there is still a significant opportunity to analyse a range of alternative futures and plan accordingly.

A range of formalised analytical methods were developed as tools to analyse and plan for risk, ranging from relatively qualitative, scenario-based approaches which creatively explore a range of possible futures (Kahn & Wiener 1967; Wack 1985; Schwartz 1991; Godet 1994; van der Heijden 1996; Alcamo 2001), to relatively quantitative, probabilistic approaches that sought to quantify the probability and consequences of a range of outcomes (US Nuclear Regulatory Commission 1975; Kaplan & Garrick 1981; Morgan 1992; Vose 2008). The concepts and methods were subsequently adapted for application to energy planning (Hirst & Schweitzer 1989; Allan & Billinton 1992) and water planning (Goicoechea, Krouse & Antle 1982; IWR-USACE 1992).

The strength of this new paradigm was that it provided a more sophisticated means for mapping and preparing for a range of probable futures. In doing so, the paradigm facilitated the explication and analysis of subjective judgements regarding acceptable levels of risk, and the identification of more effective and efficient risk management interventions.

However, the conceptual paradigm of risk management retained some critical limitations. On a conceptual level, risk was largely characterised and analysed in passive terms. Specifically, the conceptual model of risk conflates the probability and severity of a hazardous event with the ability of the social systems to effectively respond to that hazard – subtly reducing the agency of the decision-maker (Cardona 2003).

This limitation has driven calls for an expanded conceptual model for risk based around the related notion of vulnerability (Adger 2006). In this new conceptual model, risk is defined as the product of a hazard (defined by its probability and severity) and the vulnerability of the system to that hazard – thereby separating the assessment of the external threat from the assessment of the system's response (Cardona 2003).

However, even the extended framework of vulnerability management remains largely defensive in stance, typically assuming that external change is a threat rather than an opportunity.

Furthermore, conventional risk assessment approaches have been criticised for failing to conceptualise and analyse systemic risk (Danıelsson 2002). As stated earlier, conventional risk assessment approaches were originally developed to assess and manage the risks associated with technological projects, particularly nuclear, chemical and aerospace projects. As such they were designed for analysing discrete technological failures. However, their performance can deteriorate when applied to complex, adaptive systems. Significantly, conventional risk assessment approaches can overlook complex interactions within systems with many components, while simultaneously missing systemic solutions.

This thesis argues that energy and water planners need a more systemic conceptual model for understanding and analysing variability and uncertainty.

2.1.4 Planning for resilience

The concept of resilience was first proposed in the 1970s (Holling 1973), but only received widespread attention outside the ecological discipline in the late 1990s and 2000s (Folke 2006). As distinct from the paradigm of planning for risk, the resilience paradigm emphasises that surprise is inevitable and sometimes it is more effective to adapt and possibly even exploit the opportunities arising from change rather than resist them.

Although the rhetoric of adaptive management, flexibility and resilience has been popular among infrastructure planners (Boin & McConnell 2007) its operationalisation in analytical processes has been limited. This has been due partly to confusion regarding what precisely 'resilience' means, with significant definitional ambiguity in the ecological literature (Grimm & Wissel 1997; Brand & Jax 2007). This ambiguity has only increased as the concepts have been adopted and translated into a wide number of disciplines (Klein, Nicholls & Thomalla 2003; Blackmore & Plant 2008).

The slow operationalisation of resilience concepts in planning practice may also be attributed to the difficulty in quantitatively assessing the relative resilience of systems. A set of advanced analytical methods, including Bayesian decision analysis and real options analysis[2], have been proposed as prospective analytical methods for assessing resilience (Borison & Hamm 2005; Borison & Hamm 2008), however their analytical complexity remains a significant challenge to their widespread use.

At a deeper level this thesis proposes that the resilience paradigm has been restricted by the underlying tensions it has with more conventional risk management concepts and methods. Similar to the tensions already identified between the paradigms of economic efficiency and physical scarcity, the resilience discourse has not yet elaborated the strengths and effective role of risk management concepts and methods in the context of resilience planning.

[2] Bayesian decision analysis and real options analysis are analysed in Section 5.4.

This thesis argues that an improved synthesis of resilience literature is required to establish a deeper understanding of the relevant concepts and analytical methods, while reconciling the different stances of the risk and resilience paradigms.

2.1.5 Discussion

The above review has characterised the development of formal urban water and energy planning as a succession of conceptual paradigms or 'waves'. Each wave may be interpreted as revealing new insights that address the limitations of previous thinking. This is perhaps most evident in the emergence of resource scarcity and environmental concerns after the critical omissions of the economic productivity paradigm. It can also be observed most recently in the take-up of resilience concepts as a response to the perceived limitations of the risk management approach.

Taking a long view of the emergence of these paradigms, it is clear that each wave has brought important new nuances to the conceptualisation of systemic performance.

A more integrated perspective is called for that reconciles the paradigms and recognises the insights and effective roles of these diverse perspectives.

2.2 The city as a living system: reviewing alternative models for conceptualising cities

2.2.1 Introduction

Cities are much more than human artefacts or machines. They are living systems that evolve in response to the populations they support and the ecosystems in which they are embedded.

The idea of conceptualising cities as living systems is certainly not new, so this section continues by reviewing the application of living systems models to understanding and analysing cities. The review highlights a significant gap between the conceptual models developed and applied to cities and societies and the conceptual models in the disciplines from which they claim to draw – suggesting a clear opportunity for deeper interdisciplinary learning and insight.

2.2.2 The city as an urban ecological system

The concept of the city as a living system was first proposed by Abel Wolman in his book *The Metabolism of Cities* (1965). Wolman used metabolism as a metaphor to liken the city and its material and energetic fluxes to the metabolic fluxes of an organism. He also used the concept as a model to identify and quantify the material and energetic inputs and waste outputs of a hypothetical American city. In so doing, Wolman sought to draw attention to the scale of material and energetic throughput of cities and, by extension, the depletion of resources and the environmental impact of waste materials.

The work stimulated a series of modelling exercises in the 1970s and 80s by various academics to better quantify the flows of food, water, material and fuel inputs through to their subsequent disposal in landfills, oceans and the atmosphere for the cities of Miami (Zuchetto 1975), Tokyo (Hanya & Ambe 1976), Brussels (Duvigneaud & Denayeyer-De Smet 1977), Hong Kong (Newcombe et al 1978) and Paris (Odum 1983), among others (Kennedy, Pincetl & Bunje 2011).

The concept received widespread popularity in the 1990s with the growing dialogue on sustainability and the increasing formalisation of material flow analysis. Key works in this period included Baccini and Brunner's 'Metabolism of the Anthroposphere' (1991), which developed a rigorous and well documented process for modelling the urban metabolism (Brunner & Rechberger 2003). Another important contributor to the field was Herbert Girardet (1992) who contributed the distinction between circular and linear metabolisms – a notion that received widespread traction in the urban metabolism discourse where previously the focus had been dematerialisation alone.

Although the metaphor and model of the urban metabolism has contributed important insights to the study of cities they are not without limitations. Despite the concept's biological origins, the metaphor has largely given rise to a mechanistic model for conceptualising cities. Critical insights of ecological thinking, including the importance of feedbacks and threshold effects, are largely excluded (Golubiewski 2012), and the complex interactions between human systems and natural systems are largely simplified to the point where natural systems are viewed as sources or sinks for human activities. Furthermore, important insights regarding the temporal and spatial heterogeneity of ecosystems and other structural mechanisms are largely excluded (Pickett et al. 2011). The field has also been more broadly criticised for lacking deep interdisciplinary learning from the disciplines it claimed to be drawn from (Rapaport 2011).

The concept of the urban ecological system or urban ecosystem arose as a response to the perceived limitations of the urban metabolism metaphor and models (Pickett et al. 1997). From its original description by Arthur Tansley in 1935, the ecosystem concept highlighted the close coupling and complex interactions of human systems with their environments:

> We cannot confine ourselves to the so-called 'natural' entities and ignore the processes and expressions of vegetation now so abundantly provided by man. Such a course is not scientifically sound, because scientific analysis must penetrate beneath the forms of the 'natural' entities, and it is not practically useful because ecology must be applied to conditions brought about by human activity. The 'natural' entities and the anthropogenic derivatives alike must be analysed in terms of the most appropriate concepts we can find (Tansley 1935, p. 304).

However, despite Tansley's urgings the field of ecosystems ecology has almost exclusively focussed on natural ecosystems or, in some cases, the natural elements of human-impacted ecosystems until its adaptation in urban ecology in the late 1990s and 2000s (Pickett et al. 1997; Grimm et al. 2000; Pickett & Cadenasso 2002; Pickett et al. 2011).

The urban ecology field has been proposed as a fresh slate for engaging more deeply with ecological theory in the analysis of cities. For instance, ecological theory emphasises an important duality between the 'function' or processes that govern a system and its behaviour on the one hand, and the 'structure' or configuration of a system and how this impacts its behaviour and performance on the other. While the models and metaphors of urban metabolism served well to highlight the functional characteristics of systems, they simultaneously obscured important structural patterns observed by ecologists (Ehrenfeld 2004; Pickett et al. 2011).

For instance, important insights may be drawn from a rigorous translation of patch dynamics (Grimm et al. 2000) – a branch of ecosystems theory exploring the role of spatial heterogeneity, hierarchy and other structural patterns in resisting disturbance (Pickett et al. 1989). Similarly, the ecological resilience literature has been identified as a critical body of theory for incorporation (Alberti & Marzluff 2004; Pickett, Cadenasso & Grove 2004; Pickett et al. 2011; Pickett et al. 2013).

The urban ecological systems concept has also been presented as an ideal bridge between the disciplines of ecology and economics (Golubiewski 2012). However, the field of urban ecology has not focussed on economic theory. In particular, it has not considered key innovations in conceptualising and analysing coupled ecological economic systems (Costanza et al. 1993) – a critical body of theory in policy setting (Shi 2004).

2.2.3 The city as an ecological and economic system

The notion of integrating ecological and economic systems has a long history going back to the formalisation of both disciplines (Lotka 1925; Cleveland 1987), however the modern discipline of ecological economics is largely descended from several seminal works exploring the interactions between economic and ecological systems (Boulding 1966; Meadows et al. 1972; Daly 1973; Daly 1977; Costanza, Perrings & Cleveland 1997; Røpke 2005), culminating in the discipline's formalisation in the late 1980s and early 1990s (Costanza & Daly 1987; Proops 1989; Costanza 1991; Common & Perrings 1992; Costanza & Daly 1992; Røpke 2005).

A central notion of the discipline is that economies are open systems that depend on and are ultimately limited by their supporting ecological systems. As such, the discipline holds that economic analysis and planning should incorporate physical and biological processes to ensure economic activities do not undermine these supporting ecological systems and, by extension, their long-term sustainability.

Over time a progressively nuanced model emerged for the so-called 'coupled ecological-economic system' (Costanza et al. 1993; Costanza, Perrings & Cleveland 1997; Berkes, Colding & Folke 2003). These systems were characterised as complex, adaptive living systems that need to be studied in an integrated conceptual and analytical framework. A key element of this model was a recognition of threshold effects or non-linear dynamics, where a small incremental change in the extraction of a resource can lead to irreversible changes in ecological function and structure – providing a clear argument for a qualitatively different conceptualisation of sustainability based on the ecological concept of resilience (Common & Perrings 1992; Perrings 1997).

The notion of an integrated ecological-economic system found practical application in analysing alternative responses to climate change. A field of inquiry, termed integrated assessment, sought to form coherent, integrated models for society and the ecosystems in which they are embedded (Parson, Fisher-Vanden & Karen 1997; Schneider 1997).

Despite significant progress the fields of ecological economics and integrated assessment have struggled with several key conceptual and analytical challenges. For instance, there has been considerable debate around the extent to which environmental and social impacts should be monetised (Funtowicz & Ravetz 1994; Ecological Economics 1998; O'Connor 2000; Ackerman et al. 2009). In response, some integrated assessment practitioners have advocated a target-driven approach based on the relative cost effectiveness of alternative policies (Ackerman et al. 2009).

Integrated assessment practitioners have also struggled to effectively incorporate stochastic behaviour and uncertainty (Boulanger & Bréchet 2005; Ackerman et al. 2009). This has been partly due to challenges in reconciling competing epistemological stances to uncertainty (Rotmans & Van Asselt 2002). Some integrated assessment practitioners advocate a probabilistic approach in which uncertainties are quantified using probability distributions (Tol 2003). The central argument for such an approach is that, whether they are explicitly recognised or not, probabilities are assigned, and expressing them quantitatively is preferable on the grounds of transparency. Others argue that probabilistic approaches systematically exclude key ecological concepts including non-linearity, threshold behaviour, irreversibility and path dependence, leading to results that systematically underestimate the risks of low probability but highly catastrophic events (Van den Bergh 2004; Weitzman 2009). In response, they advocate an 'insurance-based' stance in which a range of scenarios are elaborated, including low-probability but catastrophic scenarios.

More generally, integrated assessment studies have been limited by their focus on highly aggregated systems (Rotmans 2006). At such scales, it is difficult to analyse the mechanisms underlying resource consumption, and the implications to policy-making are correspondingly unclear. There is therefore a significant opportunity in connecting this body of theory to the study of urban systems in general and urban water and energy systems in particular.

2.2.4 Discussion

As demonstrated in the review above, a robust academic discourse has already developed around conceptualisations of the city as a living system. The discourse has grown from the application of the organismic metaphors of the urban metabolism to the more modern, theoretically-informed models of the city as an urban ecological system.

However, the review has demonstrated that the conceptual models of urban metabolism and urban ecology are still a work in progress. Key opportunities for improvement include the translation of theories of ecological structure and resilience. Furthermore the field is yet to deeply engage with economic theory – a critical element if the field is ever to bridge the gap between theory and practice.

Turning to the field of ecological economics, the review found a rich discourse on the opportunities and challenges of integrating the disciplines of ecology and economics. In so doing, the review has identified a set of critical conceptual and analytical divisions that are still in the process of being resolved.

A central hypothesis of this thesis is therefore that the two systems disciplines of economics and ecology, if brought together, might offer useful insights which could contribute to the analysis and design of urban infrastructure systems. What is missing, this thesis argues, is a synthesis and integration of the relevant concepts and methods from both disciplines to form a coherent conceptual and analytical framework.

2.3 Research questions and approach

2.3.1 Research question 1

Rationale

The review above has highlighted:

1. a series of limitations and tensions in the performance concepts underlying energy and water planning that are inhibiting a more integrated perspective, and
2. a set of opportunities for improving the conceptualisation of cities as living systems

In so doing, the review has revealed there is a clear opportunity to return to the theoretical literature in the systems disciplines of ecology and economics in order to seek a deeper interdisciplinary synthesis.

Research question 1 therefore focuses on the suite of concepts identified as underlying systemic performance in ecology and economics.

Research question

What attributes and mechanisms have been observed to underlie systemic performance in ecology and economics?

- **a) What are the key drivers for systemic performance?**
- **b) What characteristics are required for systemic performance?**
- **c) What mechanisms underlie the development of those attributes?**

Approach

The conceptual analysis will be based on two key approaches.

Firstly, the analysis will adopt a consilience-based approach. Consilience is a claim of scientific validity whereby a scientific finding may be said to be stronger if it has been arrived at by the convergence of two or more independent sources of evidence (Wilson 1999).

As stated earlier, ecology and economics are the two key disciplines concerned with analysing and theorising the behaviour of complex, adaptive systems. However, barring the fields reviewed above, these fields have developed relatively independently, and have drawn from distinct bodies of empirical evidence. As such, there is a significant opportunity to compare and contrast the two fields for the purpose of forming a more robust and integrated conceptual synthesis.

Secondly, the conceptual analysis will adopt a historical stance. The analysis attempts to synthesise a vast body of literature from two disciplines, each with a deep and diverse history, and the concepts that are currently the subject of inquiry represent a small fragment of a conversation that spans over a hundred years. Furthermore, specific concepts have emerged in waves that are often the subject of heated debate for a decade or so and then go largely quiet for half a century, only to re-emerge to prominence. These later interpretations are often coloured by the thinking of the time and can miss key insights offered by the original authors. A literature review of the current literature alone would therefore provide a biased map of ecological and economic thought.

The conceptual analysis will therefore identify a suite of clusters of concepts identified in the literature and trace them back to their formalisation, which in some cases goes as far back as the 19th century. The analysis will then trace the emergence and development of each concept to the present to provide a richer perspective of their nuances and ambiguities.

Based on this analysis the myriad concepts will be synthesised into a relatively focussed set of concepts for analysing and describing systemic performance

2.3.2 Research question 2

Rationale

Having established a framework of concepts for describing systemic performance, the thesis will then analyse whether this framework provides novel and significant insights into the urban water and energy planning contexts, and whether these insights are of sufficient value to justify the effort of their adoption.

Research question 2 therefore explores the relevance and implications of the conceptual framework in the context of urban water planning and energy planning.

Research question

> **How do the concepts of systemic performance meaningfully translate to the planning and design of urban water and energy systems?**
>
> **a) How do the concepts differ from those applied in energy and water planning?**
>
> **b) What significant new insights do they offer?**

c) **How could those insights translate to tangible changes in the design of energy and water systems?**

Approach

The broad approach for answering this question will be to trace through each of the concepts identified in the conceptual framework and identify similar concepts, practices and design patterns in energy and water planning. The key focus of the review will be to identify similarities and differences between the conceptual framework and the concepts and design patterns that have arisen in energy and water planning. Where alignment is observed between existing practices and the identified concepts, the analysis will explore whether the findings of the conceptual synthesis could refine or contextualise existing practices. Where gaps are observed, the analysis will explore whether the conceptual framework could offer novel insights or design patterns to energy and water planners and designers.

2.3.3 Research question 3

Rationale

A new set of performance concepts is of limited value if planners lack the means to assess and therefore design for those characteristics.

Research question 3 therefore focusses on identifying how systemic performance may be assessed using quantitative analytical methods.

Research question

How can systemic performance be assessed?

a) **What analytical methods are available for assessing each attribute?**

b) **What are the strengths and limitations of each method?**

c) **In what situations is each method most useful?**

d) **How can the analytical methods be combined to form coherent analytical processes?**

e) **What are the considerations guiding the formation of these analytical processes?**

Approach

The broad approach will be to investigate and assess a wide-ranging suite of analytical methods that broadly align with each of the performance concepts. The assessment will focus on identifying the strengths, limitations and effective role of each candidate method viewed from the perspective of each systemic performance concept. In doing so the analysis will seek to offer guidance on how the methods may be effectively integrated to assess systemic performance.

The review of integrated assessment above identified two key epistemological divisions: the extent to which objectives should be assigned monetary values, and the extent to which uncertainties should be quantified as probabilities. The analysis will therefore attempt to compare the differing epistemological stances on balanced terms where possible. In doing so, the analysis will seek to establish a more integrated perspective.

2.3.4 Research question 4

Rationale

Finally and critically the conceptual framework and analytical methods will need to be tested to demonstrate their feasibility, benefits, and capacity to provide a material improvement in outcomes.

Research question 4 therefore explores the practical value of the concepts and analyses in realistic problem situations.

Research question

Are the analytical methods practically useful?

a) **Do the proposed concepts lead to novel strategies?**

b) **Is the application of the analytical methods feasible in terms of analytical time and complexity?**

c) **To what extent do the concepts and methods offer a material improvement in systemic performance?**

Approach

The broad approach for addressing these questions will be to construct a series of hypothetical case studies to test the various aspects of the framework. In the absence of a real-world case study, a set of realistic problem situations will be elaborated. Although they will be fictional in detail, the situations and data will be based on a series of real consulting projects undertaken at ISF in partnership with utilities around Australia.

The case studies will be accompanied by a series of modelling examples to test the feasibility and results of the analytical methods in realistic problem situations.

The following chapter begins by addressing the first of these four research questions.

3 Concepts: a synthesis of systemic performance concepts arising from ecology and economics

3.1 Introduction

What are the fundamental attributes of systemic performance and what mechanisms contribute to their development? This question lies at the heart of both the economic and ecological inquiries and the responses are myriad.

The attributes emphasised in the dominant economic and ecological discourses are partial and largely reflect the biases in their respective intellectual pedigrees. Economic performance attributes such as gross domestic product, economic growth, productivity and competitiveness largely assess the relative vigour of economic systems and therefore their capacity to compete in the absence of resource constraints or disturbance (Hamilton 2003; Costanza et al. 2009). While ecological performance attributes such as diversity, stability, organisation, and resilience are related measures for assessing the relative robustness of ecological systems and in turn their vulnerability to human intervention (Grimm & Wissel 1997; Hansson & Helgesson 2003).

Attempts to integrate these two seemingly disparate perspectives are not new and may be traced at least as far back as the biological integrity theory of David Frey, James Karr and others (Frey 1975; Karr et al. 1986; Karr 1991, 1992), the plant strategy theory of John Phillip Grime (Grime 1977, 1979), and the ecosystem health measures of Robert Costanza and others (Costanza 1992; Costanza & Mageau 1999). However, as described in a detailed review below (see Section 3.5.2), these works have focussed on more specific system types and concepts than the ones analysed in this review, therefore limiting their application to a more general understanding of systemic performance.

This chapter significantly builds on these earlier works by re-examining, synthesising and integrating the diverse conceptions of systemic performance emerging from both ecology and economics. Given the profusion of modern literature in both fields, the review began by analysing contemporary ecological and economic literature and attempting to identify clusters of similar concepts. The key references underlying these conceptual clusters were then identified to trace their historical sources. This process was repeated until the concepts resolved into a limited set of distinct attributes. Having identified the attributes underlying the two disciplines, the process was reversed to trace the development of those fundamental concepts through time as they emerged, dissipated and re-emerged in the discourse.

In the course of this deep historical review the concepts resolved into three distinct but interrelated attributes: the capacity of a system to thrive despite resource scarcity and competition; the capacity of a system to absorb variability, fluctuation and disturbance and remain essentially unchanged; and the capacity of a system to adapt to shocks, shifts and perturbation and avoid systemic failure.

A similar emergence occurred when analysing the mechanisms underlying the attributes. Amid the profusion of concepts identified by both disciplines, two types of mechanisms were observed to underlie each attribute: one was observed to characterise the types of processes or system components, while the other broadly described the enabling patterns of the system configuration. These two types of mechanisms have been categorised as 'functional' and 'structural' respectively, borrowing from a commonly applied distinction in ecosystems ecology.

The chapter begins by exploring each of the attributes that have emerged from this exhaustive historical literature review. The attributes are addressed in turn by first identifying the drivers or imperatives (the 'why'), then elaborating their various definitions within the literature (the 'what'), and then unpacking the underlying functional and structural mechanisms toward their development (the 'how'). After describing the attributes and mechanisms, the key elements are brought together to form a new conceptual framework. The chapter concludes by analysing the strengths and limitations of this framework with respect to prior contributions.

3.2 Performance subject to scarcity and competition

3.2.1 Scarcity and competition

The disciplines of economics and ecology are both concerned with open, dissipative systems dependent on a continual flow of resources to develop and maintain their functions and structures (Bertalanffy 1950; Prigogine & Stengers 1984). However, a typical feature of ecological and economic systems is competition between rival elements of the system for access to a common resource base, thus exposing those elements to *resource scarcity* and *competition*.

Though 'competition' has a variety of definitions its application here refers to the situation where individuals or groups are potential rivals who depend on a shared resource base. For example Grime defined competition as 'the tendency of neighbouring plants to utilize the same quantum of light, ion of a mineral nutrient, molecule of water, or volume of space' (see also Harper 1961; Milne 1961; Grime 1973, p. 311; Grime 1977, pp. 1169-70).

Competition of this kind is pervasive in economic systems: rival individuals compete for wage income, goods and services; rival firms compete for consumptive income, land, labour, capital and investment; and rival nations compete for export income, capital investment and imports.

Ecological systems similarly consist of rivals competing for scarce resources: rival producer species compete for scarce sunlight, water and nutrients; rival consumer species compete for prey; while rival decomposer species compete for detritus.

The ability to withstand resource scarcity and competition therefore emerges as a key underlying driver for both ecological and economic systems.

3.2.2 The invisible hand, natural selection, succession, dominance and ascendance

The relative performance of economic systems in the face of resource scarcity and competition was the core focus of Adam Smith's famous treatise *The Wealth of Nations* (1776). In essence, Smith argued that the aggregated choices of individual self-determining consumers within a competitive market reward those producers capable of most efficiently generating goods and services from scarce resources. In so doing, those successful producers expand both their market share (i.e. the resource flows available to the individual firm) and the overall throughput of the market, leading to economic growth. Producers are therefore guided by the 'invisible hand' to efficiently translate available resources into the best value to the consumer.

Thomas Malthus (1798) extended Smith's theory by examining the relationship between economic growth and the resources on which it depends. He concluded that all economic systems in a state of growth subsist either on productivity gains (e.g. through increasing resource efficiency or intensity), or by extending their resource base (e.g. through the colonisation of new territory). Consistent with this reasoning Malthus argued that this growth must ultimately approach a physical limit.

In ecology, Charles Darwin's famous exposition on the origin of species marked the beginning of a generalisation of these theories to all living systems (1859). Drawing on Malthus' earlier work, Darwin argued that in ecological systems a similar tension occurs between the limitless growth of life and the limited capacity of the environment to sustain it. In a clear parallel to

Smith's 'invisible hand', Darwin suggested the emergent consequence of this 'struggle for existence' would be the 'natural selection' of the most effective characteristics for a given environment,

> that any being, if it varies however slightly in any manner profitable to itself, under the complex and sometimes varying conditions of life, will have a better chance of surviving, and thus be naturally selected.

Alfred Lotka later united the discourses of ecology and economics using the emerging language of systems theory (1922). From Darwin's 'natural selection' he observed two consequences: firstly, natural selection will 'give relative preponderance (in number or mass) to those most efficient in guiding available energy [and other materials]'; secondly, natural selection will 'operate to preserve and increase … suitably constituted organisms to enlarge the total energy flux through the system'. Thus, similar to the earlier hypothesis of Malthus, Lotka observed that competition results in the survival of those species most capable of extensively and efficiently exploiting the resource base.

Lotka also noted the occurrence of a shift in emphasis as a system approaches the limits of its resource base. In the early stages of ecosystem development when resources are abundant, he observed natural selection to favour those species capable of extensively exploiting free resources, while in later stages of development when free resources are relatively scarce natural selection promotes and maintains species capable of conserving and recycling resources. He was of the view that both the earlier tendency toward exploitation and the later tendency toward conservation and recirculation were consistent with a general tendency toward increasing the flux of resources through the system, which he termed the 'law of maximum flux'. In this magnificently simple insight Lotka had conceived a response to Malthus's nightmare. That is, rather than approaching a physical limit defined by pestilence and disease, mature ecological systems are capable of sustained increases in throughput by both increasingly intensive application of the available resource base and by recirculating waste resources in increasingly tight loops.

In ecology Lotka's law of maximum flux found expression in ecological succession theory (Clements, Weaver & Hanson 1926; Clements 1936). Drawing on the ground-breaking research of Cowles (1911), and prominently advocated by Frederick Clements, this school observed a developmental progression to occur from initial colonisation, through simple grazing-dominated ecosystems to forests and other complex ecosystems. Despite the abundance of resources, 'early stage' ecosystems have relatively low rates of energy and nutrient flux, while 'late stage' ecosystems sustain very high rates of energy and nutrient fluxes with negligible free resources.

Fisher (1939) and Clark (1940) independently arrived at a similar conclusion in their analysis of the development of national economies. They proposed a staged model of economic development in which economic systems followed a consistent set of developmental stages from relatively simple, primary or agricultural and mining dominated economies, through secondary or manufacturing-dominated economies to tertiary or service-dominated economies. A key implication of this developmental trend was a decreasing proportion of economic throughput sustained by primary production and an increasing emphasis on service-based industries with negligible primary material inputs (Stahel 1997).

Lotka's law of maximum flux was later elaborated as the 'principle of maximum power' by Howard Odum and Richard Pinkerton (Odum & Pinkerton 1955). By analysing an extensive array of open processes including photosynthesis, climax ecological communities and human civilisations, they similarly observed resource competition to result in the successive selection of those components capable of maximising the throughput of an open system. They also demonstrated analytically that this tendency will result in the selection of functional components with low efficiency levels in situations of abundant resources shifting toward progressively higher levels of efficiency as they approach the limits of their resource base.

Hutchinson's conception of the ecological niche (Grinnell 1917; Elton 1927; Hutchinson 1957; Whittaker, Levin & Root 1973; Patten & Auble 1981) contributed an insightful metaphor toward understanding the tendency toward increasing flux. Expressed technically, the 'fundamental niche' defines the domain or, more accurately, the multi-dimensional hypervolume of resources such as sunlight, nutrients and prey that *potentially* sustain a species in the absence of competition, while the 'realised niche' defines the resources that the species consume after exclusion by competitors.

Drawing on the ecological niche concept, the relative 'dominance' of a species or community of species was defined by its capacity to exploit the fundamental niche or 'fill the niche' and thus thrive despite resource scarcity and competition (McNaughton & Wolf 1970; Morse 1974; Schoener 1974).

The consequence of filling the niche is the successive preclusion of competitors as there is no available niche space to occupy:

> It is hard to penetrate and partition further an already intricately partitioned system. The forces to exclude, in the form of predation, competition, alleochemical defenses, and other negative interactions, are not only too great, in the conventional view, but in the systems view the puzzle of systemwide interactions is too complex a knot to unravel and consistently fit into. The climax ecosystem, with its relatively stable species list, ensues (Patten & Auble 1981, pp. 910-1)

This conceptual combination of an intensive metabolism and tightly integrated extensive structure was formally elaborated and quantified by Robert Ulanowicz in a quantitative measure of the relative stage of succession of biological communities that he termed 'ascendancy' (Ulanowicz 1980; Ulanowicz 1986; Ulanowicz 1992). This measure combined two key parameters: a measure of the flux of energy and other material flows passing through the system (note: owing to internal recirculation this is not equivalent to the inputs or outputs), and a measure of the connectedness or coherency of the system, defined as the average mutual information among the components.

In summary then, the capacity of an ecological or economic system to thrive despite resource scarcity and competition is here termed 'ascendance'. This term is broadly consistent with and encompasses the individualistic concept of 'dominance' that is used in ecology when analysing individual populations (McNaughton & Wolf 1970; Morse 1974), while the term simultaneously captures the systemic concept of 'succession' as the progressive and cooperative preclusion of competition by communities (Patten & Auble 1981, pp. 910-1). It is also broadly consistent with Ulanowicz's quantitative 'ascendancy' index (Ulanowicz 1980; Ulanowicz 1986; Ulanowicz 1992).[3]

3.2.3 Mechanisms underlying ascendance

Functional mechanisms

The first rigorous analysis of the functional basis for ascendance may be credited to Adam Smith (1776).[4] Smith emphasised that beyond colonising new territory, the key means for overcoming resource scarcity and competition was to increase the intensity with which the available resources are applied. In his famous dissection of a pin factory production line Smith suggested that productivity arises from a progressive 'division of labour' within and among firms in response to competitive pressures in industrialising economies:

---

[3] The distinction between 'ascendance' and 'ascendancy' was borrowed from resilience theory, which has applied 'resilience' as an attribute or quality, while 'resiliency' has been applied as a quantitative indicator.

[4] For earlier though less frequently cited references to the division of labour (Hillsman 1995).

> the greatest improvement in the productive powers of labour, and the greater part of the skill, dexterity, and judgment with which it is anywhere directed, or applied, seem to have been the effects of the division of labour.

In so doing, Smith had assigned specialisation a key functional role in the increasing productivity of firms and economies.

David Ricardo (1817) later elaborated the basis for specialisation in his theory of comparative advantage. Ricardo's analysis demonstrated that, even if an individual, firm or country can produce all goods more efficiently than all its potential competitors (i.e. it has *absolute advantage*), it still benefits from specialising in that productive activity to which it is best suited (i.e. that productive activity with the lowest *opportunity cost*). In so doing, Ricardo explicitly identified a theoretical basis for specialisation.

In ecology, an analogue to the 'division of labour' was identified by Charles Darwin (1859) as a progressive 'diversion of character' within and among species:

> the more diversified the descendants from any one species become in structure, constitution, and habits, by so much will they be better enabled to seize on many and widely diversified places in the polity of nature, and so be enabled to increase in numbers (Darwin 1859).

Alfred Lotka (1932) later provided a theoretical grounding to Darwin's hypothesis through a system of analytical proofs. His analysis led him to propose that two species competing for the same resources cannot stably coexist if their environmental conditions remain constant. This was later termed 'the law of competitive exclusion' (also see Gause 1932).

The law of competitive exclusion was later elaborated using the ecological niche concept (Grinnell 1917; Elton 1927; Hutchinson 1957; McNaughton & Wolf 1970; Whittaker, Levin & Root 1973; Morse 1974; Patten & Auble 1981). Drawing together a broad suite of empirical research, ecologists observed an increasing tendency toward niche 'partitioning' or 'compression' whereby competition successively narrows the niche space available to individual species, or, taken inversely, the species become more specialised at exploiting an increasingly narrow subset of physiological conditions.

However, subsequent ecological research has shown that ascendance is much more than simply competitive exclusion or successive specialisation. Critically, 'cooperative' processes also occur in response to competition (Connell & Slatyer 1977; Walker & Chapin 1987; Callaway 1995; Callaway & Walker 1997; Holmgren, Scheffer & Huston 1997). Drawing on a broad range of empirical evidence, ecologists observed that the functional activities of many species serve to release resources that would otherwise be unavailable to the system. For example, the functional processes of many fungi species have been observed to translate nutrients into a form that is readily available to trees, thereby allowing efficient nutrient recirculation. In so doing, facilitative mechanisms serve to expand the realised niche and allow increasing system flux without additional resource input.

Several broad patterns therefore emerge regarding the functional aspects of ascendance. In the early stage of development, competition drives the development of processes for harvesting still abundant free resources. As a system matures, competition for increasingly scarce free resources drives the development of increasingly efficient processes through competitive exclusion and specialisation on the one hand, and cooperative facilitation and recirculation on the other. As first highlighted by Alfred Lotka, both tendencies are characteristic of a general tendency toward selecting those components that maximise the resource flux of the system. Consistent with this tendency toward maximal flux, this mechanism is termed 'functional intensity'.

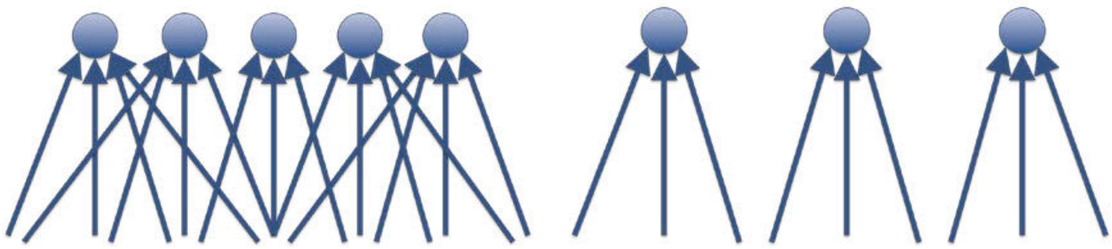

Figure 1 - Systems diagram of the functional intensity mechanism

Figure 1 provides a systems diagram of the functional intensity mechanism. The bottom of the chart represents the resource sources, the arrows represent resource flows and the top row of circles represents the system components. The system becomes more resource efficient through the differentiation of more intensive, specialised components.

Structural mechanisms

Although Smith's division of labour thesis was widely popularised, the economic discourse largely ignored the fact that he had also identified the important structural complement necessary for its full realisation. From the beginning, Adam Smith stressed that the division of labour is ultimately limited by the extent of the system and therefore its capacity to exchange materials, value and information:

> as it is the power of exchanging that gives occasion to the division of labour, so the extent of this division must always be limited by the extent of that power (Smith 1776 Book 1, Chapter 3).

John Stuart Mill also highlighted the central role of exchange in his *Principles of Political Economy*:

> The power of exchanging the products of one kind of labour for those of another, is a condition, but for which, there would almost always be a smaller quantity of labour altogether (Mill 1848 Book 1, Chapter 8).

The neoclassical economist Alfred Marshall (1890) later identified the duality of functional and structural mechanisms directly, using the language of biology. He identified two mechanisms: 'differentiation', which he used to refer to "the development of specialized skill, knowledge and machinery"; and 'integration', which he used to refer to "a growing intimacy and firmness of the connections between the separate parts of the industrial organism" (1890, pp. 240-9):

> the development of the organism, whether social or physical, involves an increasing subdivision of functions between its separate parts on the one hand, and on the other a more intimate connection between them. Each part gets to be less and less self-sufficient, to depend for its wellbeing more and more on other parts (Marshall 1890, p. 241).

The structural mechanism was subsequently elaborated to form a more comprehensive theory of economic integration. Ronald Coase (1937) formulated the important notion of 'transaction cost' and its role in controlling the degree of integration of the firm. According to Coase, transaction costs typically increase with increasing scale, whether through the increasing challenges of coordinating a large, vertically-integrated firm, or through the increasing costs of negotiating contracts between a collection of independent firms. Taken inversely, the ascendance of an economic system may be understood to arise from reconciling or overcoming the tensions between the synergies and tensions of integration.

The German economist August Lösch (1940/1954) subsequently explored the structural implications of transaction costs for regional economics. The central premise of his research was that there are economies of scale associated with production but also diseconomies of scale associated with the transportation of goods and services. Lösch argued that the consequence of the coexistence of these two forces is that each good or service will exhibit an optimum spatial scale or 'order' – for example grocery items will exhibit a low-order covering a city block, while a university education will exhibit a high-order covering an entire city. As a result the trade flows in economic systems are hierarchical, with lower order goods provided locally, while higher order goods are provided regionally.

In ecology, the biologist and early systems theorist Herbert Spencer similarly turned to interplay of functional and structural mechanisms underlying evolution in his famous System of Synthetic Philosophy. Spencer observed:

> The divisions and subdivisions of function, become definite as they become multiplied, do not lead to a more and more complete independence of functions… but by a simultaneous process they are rendered more mutually dependent. While in one respect they are separating from each other, they are in another respect combining with each other. At the same time they are being differentiated they are also being integrated (Spencer 1898, p. 205).

The analysis of the structural mechanisms underlying ascendance was later enhanced with the emergence of the 'food web' concept (Elton 1927; Lindeman 1942). First popularised by Charles Elton (1927), the food web depicts the flows of energy and other materials within an ecological community from producers (i.e. autotrophs) that translate light and heat and translate to chemical forms, through consumers that successively dissipate energy in the form of heat.

In a clear parallel to Coase's notion of the transaction cost, Raymond Lindeman (1942) observed that energy and other resources are dissipated through successive stages of the food web owing to respiration and other losses. Furthermore, in a parallel to Lösch's theory of regional development, a tendency was observed whereby consumers higher up the food chain relied on a wider range of prey than consumers lower down the chain, leading to a hierarchical structure. The level of integration of the food web is therefore fundamentally limited by the rate of losses associated with the exchange of energy, nutrients and other critical resources.

Robert Ulanowicz (1986) added further nuance to the mechanism in his analysis of ecosystem growth and development. He identified two types of losses associated with exchange: 'dissipation', which represents the system-level effect of transfers at lower hierarchical levels; and 'tribute', which characterise the system's contribution to supra systems. He noted that rewards do not necessarily arise from reducing tributes, if the overall flux of the supra system is reduced and the cycled feedbacks deteriorate.

A complex, multi-scale perspective therefore emerges for the assembly of ecological components into ascendant systems. On the one hand systems systematically reduce the losses associated with exchanges among system components while on the other hand they maximise the synergies arising from integration.

This mechanism by which components are connected to form synergistic assemblies will be termed 'structural integrity', broadly consistent with the terminology applied in economics.

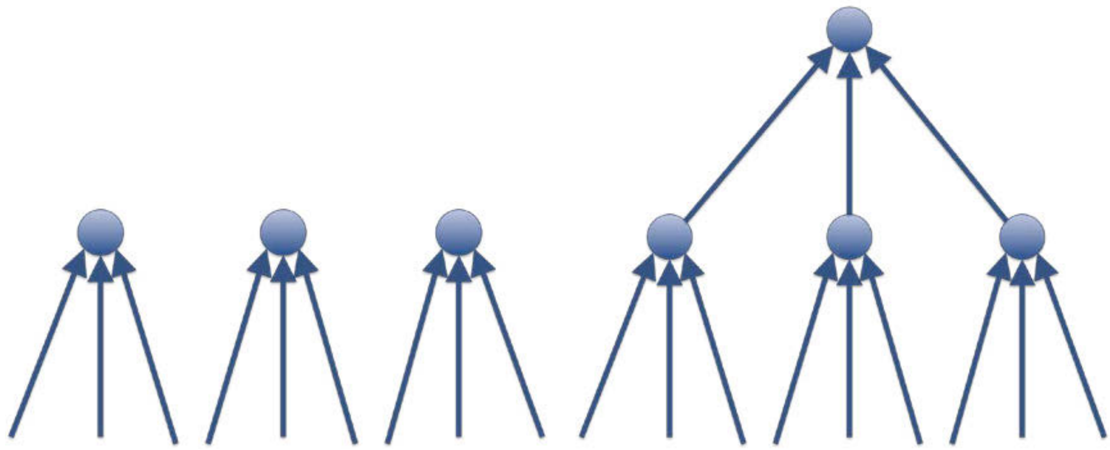

Figure 2 - Systems diagram of the structural integrity mechanism

Figure 2 provides a systems diagram of the structural integrity mechanism. The new upper row represents components at a higher spatial, temporal or functional scale. The top component enhances the scope and resource intensity of the system by tightening the circulation of resources and in turn facilitating new niche space.

This thesis therefore suggests that the ascendance of a system that is subject to resource scarcity and competition arises from a duality of mechanisms: the progressive differentiation of intensive functional components (here termed 'functional intensity') and the connection of functional components to form extensive, synergistic assemblies (here termed 'structural integrity').

3.3 Performance subject to variability and fluctuation

3.3.1 Variability and fluctuation

The mechanisms outlined above may each be understood as an optimal response to a specific set of environmental conditions. However, those conditions will typically fluctuate, thus subjecting the system to *disturbance*.

‘Disturbance’ is here used in its ecological sense to connote ‘any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment’ (Pickett & White 1985, pp. 6-9; also see Rykiel 1985; Forman & Godron 1986; Andel et al. 1987). More generally therefore, disturbance may be taken to imply a fluctuation in the driving variables of a system (or dynamic thereof). Disturbance has also been quantified as a combination of spatial extent, temporal period, and magnitude or intensity (Glenn-Lewin & van der Maarel 1992).

Economic systems are consistently subject to ‘business cycles’ and fluctuations (disturbances) occurring over various temporal or spatial scales. Similarly, ecological systems are subject to diurnal, seasonal and inter-annual ‘rhythms’ and random fluctuations in their driving variables including insolation, rainfall, temperature, wind, erosion and predation.

3.3.2 The great stability debates, inertia, regulation and resistance

The capacity of economic systems to attenuate and absorb fluctuations was the subject of considerable scrutiny following the Great Depression of the 1930s. Based on the acute unemployment experienced during the period, John Maynard Keynes (1936) sought to develop a model for the fluctuations of the business cycle and, in so doing, devise a basis for reducing them. Keynes understood the instability of the business cycle as predominantly a response to the asynchronous and inaccurate response of aggregate demand to disturbance owing to time lags and crowd behaviour. Keynes thus implied that there was a role for governments in regulating these fluctuations and thereby reducing the eccentricities of the market.

Several prominent economists later sought to advance alternative models to explain the response of economic systems to disturbance. Key contributors included Milton Friedman (1948, 1968), who emphasised fluctuations in the money supply; Friedrich Hayek, who emphasised inaccurate and asynchronous fiscal and monetary interventions; and Robert Lucas (1972), who emphasised exogenous fluctuations and their interactions with the complex microeconomic dynamics of the economic system.

A complex model of economic stability emerged in which the dynamics and structure of the economic system either magnified or dampened disturbances. Though each specific theory concentrated on different sources of economic instability, they all pointed to the benefits of a relatively stable economic system with synchronous and accurate feedbacks to the fluctuations of a dynamic environment. Thus the ‘stability’ of economies emerged as a defining attribute of optimal systemic performance.

The stability of systems subject to disturbance emerged in the ecological discourse over a similar period for quite different reasons. Though the dominant succession paradigm of the period treated disturbance largely as an aberration (Clements 1916; Clements, Weaver & Hanson 1926; Clements 1936), the ecologist Henry Gleason advanced an 'individualistic conception' in which the disturbances experienced by a living system were central to their development (Gleason 1926, 1927, 1939). Rather than viewing disturbance as an unusual phenomenon predominantly due to human intervention, Gleason emphasised that the environment of a biological system varies continuously in time and space. Gleason's theory therefore suggested that the components of the system must each be uniquely adapted to the specific disturbances comprising its unique realised niche.

The role of disturbance in the development of ecological systems rose to popular prominence during the great stability debate which began in the 1950s (see e.g. McCann 2000). Observing the increasing deterioration of ecosystems globally, several prominent ecologists advanced differing theories for the basis of the stability of ecosystems. These included speculations on the role of biodiversity in the relative stability of ecosystems (Odum 1953; Elton 1958), and an alternative set of theories about the connections that occur between species (MacArthur 1955; Margalef 1958; Leigh 1965).

In the course of this heated debate, academics advanced a broad range of concepts in an attempt to better define stability. For instance Murdoch delineated two characteristics of this capacity: 'inertia', defined as '[the] tendency for a population to resist pressure to follow changes in … environmental factors' (Murdoch 1970, p. 500); and 'regulation', defined as 'the convergence to a single density by subpopulations which have been manipulated previously to different densities' (Murdoch 1970, p. 497). A similar set of attributes were proposed by Gordon Orians when he defined 'inertia' as 'the ability of a system to resist external perturbations' and the new term 'elasticity' as 'the speed with which the system returns to its former state following a perturbation' (Orians 1975, p. 141).[5]

To differentiate these attributes from the recently coined 'resilience' (Holling 1973), Boesch introduced the concept of 'resistance' which he defined as 'the ability of the ecosystem to

[5] Note both Orians and Pimm use the term 'perturbation' interchangeably with the concept of 'disturbance' defined in this chapter, however this thesis adopts a strict delineation between these two terms whereby disturbance involves a change in the driving variables of the system but not necessarily a significant in its state variables, while perturbation involves a change in the state variables of the system owing to a shock or shift beyond its attenuation and absorption capabilities (see e.g. Mandeville 1714; Hume 1739). For further clarification see the definitions for disturbance (Section 3.3.1) and perturbation (Section 3.4.1).

withstand stress without change' (Boesch 1974, p. 109). Webster, Waide and Patten suggested a similar definition of resistance as 'the ability of an ecosystem to resist displacement' (Webster, Waide & Patten 1975, p. 1). And Lepš et al. similarly defined resistance as 'the ability of a system to avoid displacement during a stress period' (Lepš, Osbornova-Kosinova & Rejmanek 1982, p. 54). Preferring a much more confined definition, Pimm defined 'resistance' as 'the degree to which a variable is changed, following a perturbation' (Pimm 1984, p. 322).[5]

Based on an extensive review of stability concepts in ecology, Grimm and Wissel observed that in the process of seeking analytical tractability much of the original emphasis of the stability concepts had been lost, while the more general term 'stability' had become a catch-all for a large cluster of often conflicting concepts, limiting its value. They therefore preferred the more general definition for resistance as 'staying essentially unchanged despite the presence of disturbances' (Grimm & Wissel 1997, p. 325) and assigned distinct terms to refer to the more analytically tractable concepts such as 'elasticity'.

Although 'stability' is the most commonly applied term for this cluster of concepts in economics, this thesis follows Grimm and Wissel and avoids using the term. In its place this thesis applies the more technical, ecological term 'resistance'. Broadly consistent with its original definition and the subsequent review by Grimm and Wissel, resistance is defined here as the capacity of a system to absorb variability, fluctuation and disturbance while remaining essentially unchanged (Boesch 1974, p. 109; Webster, Waide & Patten 1975, p. 1; Lepš, Osbornova-Kosinova & Rejmanek 1982, p. 54; Grimm & Wissel 1997, p. 325).

3.3.3 Mechanisms underlying resistance

Functional mechanisms

The first explicit statement of the functional basis for the resistance of economic systems appears in a famous text by the economist Alfred Marshall:

> A district which is dependent chiefly on one industry is liable to extreme depression, in case of a falling-off in the demand for its produce, or of a failure in the supply of the raw material which it uses. This evil again is in a great measure avoided by those large towns or large industrial districts in which several distinct industries are strongly developed. If one of them fails for a time, the others are likely to support it indirectly; and they enable local shopkeepers to continue their assistance to workpeople in it (Marshall 1890, p. 273).

Myriad attempts followed to test Marshall's hypothesis using a wide sequence of indices for both diversity and stability, and a correspondingly broad range of temporal and spatial scales (McLaughlin 1930; Tress 1938; Reinwald 1949; Rodgers 1957; Conroy 1975; Kort 1981; Brewer 1985; Brown & Pheasant 1985; Attaran 1986; Smith & Gibson 1988; Kurre & Weller 1989; Neumann & Topel 1991; Malizia & Ke 1993; Hunt & Sheesley 1994; Siegel, Johnson & Alwang 1995). This work led, perhaps unsurprisingly, to a diversity of conclusions, particularly in earlier years.

The debate was considerably advanced by a parallel conceptual development in financial theory (Markowitz 1952; Treynor 1961; Sharpe 1964; Lintner 1965; Mossin 1966). So-called 'modern portfolio theory' established the analytical justification for investment portfolio diversification. Specifically, the theory demonstrated how the volatility and risk exposure of investment portfolios can be reduced by combining investments that are sensitive to different variability and fluctuations (i.e. combining investments with minimal or negative 'portfolio covariance').

With time and a great deal of controversy a degree of consensus emerged that economic stability was correlated with specific kinds of industrial diversity. Specifically, the more conclusive studies (e.g. Conroy 1975; Brewer 1985; Brown & Pheasant 1985; Kurre & Weller 1989; Hunt & Sheesley 1994; Siegel, Johnson & Alwang 1995) applied a measure of diversity similar to the financial portfolio covariance measure, rather circuitously reaffirming Marshall's original hypothesis. That is, for an economy to have resistance it needs more than a richness of industrial groups per se, it requires a specific kind of functional diversity involving industries with differing responses to the disturbances to which they are exposed.

The mechanism first emerged in the ecological discourse from a series of empirical observations of an apparent coincidence of community stability and a richness of species (Odum 1953; Elton 1958). Once again, after a great deal of debate spanning several decades, several competing measures of diversity emerged, referring variously to response type structure, physiology, life strategy, symbiotic associations, and the spatial and temporal domain of the species' functions or interactions. These measures were later understood as different ways of characterising the sensitivities of populations to specific disturbances and were unified under the concept of 'functional diversity' (Friedel, Bastin & Griffin 1988; Körner 1994; Gitay & Noble 1997; Lavorel et al. 1997; Loreau 2000; Loreau et al. 2001). The diversity concept was later clarified as a richness of response types within each functional role type sustaining a community or ecosystem (Diaz & Cabido 2001; Elmqvist et al. 2003).

For the purposes of this synthesis, this diversification of functional components to promote a range of sensitivities to the suite of probable disturbances will be termed 'functional diversity', consistent with the term's use in ecology.

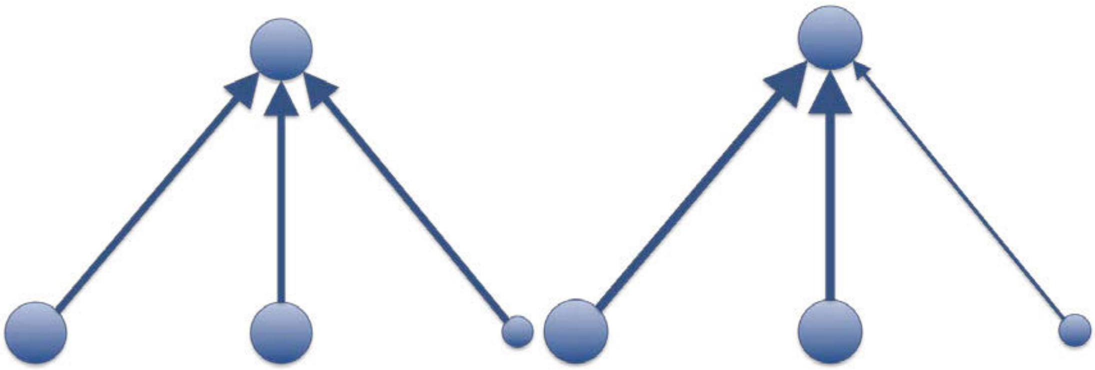

Figure 3 - Systems diagram of the functional diversity mechanism

Figure 3 provides a systems diagram of the functional diversity mechanism. A fluctuation in the resource base doesn't affect the component owing to its ability to draw resources from other unaffected resource sources.

Structural mechanisms

Alongside functional diversity, both the ecological and economic disciplines have identified an important structural mechanism underlying resistance to fluctuation and disturbance.

Perhaps the first apparent suggestion of a structural basis for resistance in the economic discourse was proffered by John Maynard Keynes when he indicated a regulatory role for governments in mitigating the fluctuations in economic activity (Keynes 1936). Specifically, by stimulating the economy during periods of recession and depressing the economy during boom periods, Keynes suggested the spending of the government suprasystem can act as an 'automatic stabiliser' or negative feedback in regulating the eccentricities experienced by the economy.

However, the structural mechanism underlying this stabilisation effect was largely ignored until its emergence in the field of regional economics. Specifically, several economists (Wundt & Martin 1993; Siegel, Alwang & Johnson 1994, 1995; Siegel, Johnson & Alwang 1995; Wagner & Deller 1998) observed that economic exchange among industries (i.e. 'industrial connectance'), as analysed by input-output analysis (Leontief 1966; Dietzenbacher & Lahr 2001), was strongly correlated with economic stability. Furthermore, they found that industrial connectance, when combined with the new portfolio diversity measures (see above), was an improved predictor of the relative economic stability of cities, regions and states (Wagner 2000).

However, the structural mechanisms underlying resistance are more complex than connectance among components alone, as demonstrated in the review of ecological literature below.

In the ecological discourse a broad outline of the mechanism first emerged from observations of the regulatory influence of predators on the fluctuations of populations (Elton 1927, pp. 117-23). Specifically, by preferentially targeting more abundant prey populations, predators act as a negative feedback to fluctuations in its various prey populations, giving rise to a more resistant network where both predator and prey can better withstand disturbance.

With time, these observations evolved into a broadly accepted principle that relatively connected biological communities not only preclude competition as described above but also possess an inherent stability when subjected to disturbance (Odum 1953; Elton 1958; Leigh 1965).

Though it was initially supported by analytical modelling (MacArthur 1955; Margalef 1958), subsequent studies revealed that the connectance hypothesis was a partial description of a far more complex phenomenon. Using an extensive series of modelling experiments Robert May and others (Gardner & Ashby 1970; May 1972; Smith 1972; May 1973) found that connectivity could be as much a source of instability as stability. May speculated that natural systems must therefore possess special network configurations that are uniquely coupled to the disturbances in their environments, however any further nuances in the form of that configuration remained elusive.

Samual McNaughton later provided a clarified hypothesis based on a detailed review of the debate:

> If a resource state fluctuates in time or space as it does in nature, functional properties of a community consisting of distinct and non-overlapping adaptive ranges will fluctuate wildly while a community consisting of species with overlapping ranges will remain more constant as declines in one species are compensated by increases in others (McNaughton 1977).

As later demonstrated analytically by Donald DeAngelis (1992) and others (McCann, Hastings & Huxel 1998), the spatially and temporally nested assembly of highly connected biological communities facilitates a form of negative feedback, which dampens the fluctuations experienced at any particular time and space. The basis for the mechanism is that each component of a system is sensitive to a specific spatial and temporal domain of disturbances (i.e. referred to in patch dynamics as a specific 'patch' and 'rhythm'). The greatest dampening benefit among components will therefore arise from the interaction of components with different spatial and temporal scales. On the other hand, the connection of components with different spatial and temporal domains, but similar spatial and temporal scales, will provide a smaller benefit. These two effects lead to a nested assembly whereby connections among components with similar spatial and temporal scales (i.e. 'horizontal connections') are relatively weakened while connections between components with quite different spatial and temporal scales are relatively strengthened.

The consequence is a complex, nested network capable of effecting compensating feedback. This mechanism will be termed 'structural complexity', consistent with the term's use in ecology.

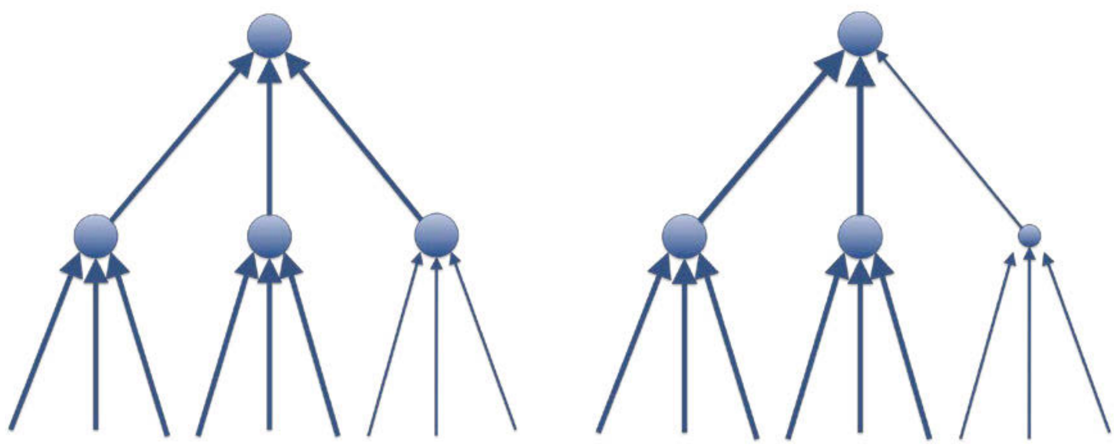

Figure 4 - Systems diagram of the structural complexity mechanism

Figure 4 provides a systems diagram of the structural complexity mechanism. The right middle component survives despite a fluctuation affecting its resource source owing to its ability to reduce its tribute resource flow to its higher order component – a form of compensatory feedback.

In summary, the resistance of a system to disturbance has been described as emerging from a duality of mechanisms: the diversification of functional components with different sensitivities to the suite of probable disturbances (here termed 'functional diversity') and the assembly of functional components within complex, nested networks capable of effecting compensatory negative feedback (here termed 'structural complexity').

3.4 Performance subject to shocks and shifts

3.4.1 Shocks and shifts

The attributes identified above constitute responses which act to maintain the metabolism and local stability of a system when it is subjected to resource scarcity, competition and disturbance. However, economic and ecological systems are also subject to surprise shocks and shifts in their conditions, making a change in the state variables of the system or *perturbation* both inevitable and quite often desirable.

Perturbation is here used in its specific ecological sense as 'a departure (explicitly defined) from a normal state, behaviour, or trajectory (also explicitly defined)' (Pickett & White 1985, pp. 5-6; also see Rykiel 1985). More generally, perturbation implies a shift in the functional or structural state variables of a system (or dynamic thereof) and is often associated with surprise shocks or shifts in the driving variables of the system.

S*urprise* is here used in a technical sense to imply a disturbance experienced as novel by a system, that is, a disturbance outside the temporal or spatial memory domain of a system (see also Brooks 1986; King 1995; Kates & Clark 1996).

All economic systems are subject to surprise shocks and shifts in conditions including new technologies, stock market crashes, or disruptions to resource availability. Such shocks and shifts are difficult to anticipate and often necessitate structural change. Similarly, all ecological systems are occasionally subject to shifts in conditions including invasive species and climate change.

The capacity to effectively adapt to surprise shocks and shifts in conditions emerges as the third key concern in the ecological and economic literature.

3.4.2 Creative destruction, adaptability and resilience

The role of perturbation in the development of economic systems was first popularly analysed by the economist Joseph Schumpeter (1911/1934). Schumpeter understood economic systems as continuously subject to destabilising innovations that repeatedly stimulate 'creative destruction' or forced structural realignment within the economic system. The relative performance of economies was therefore reliant on continuously initiating and adapting with this change, a capacity that Schumpeter saw as the principal role of the entrepreneur.

The Austrian economist Friedrich von Hayek similarly understood economic changes as fundamental to economic inquiries: ‘economic problems arise always and only in consequence of change’ (Hayek 1945, p. 523). Thus Hayek understood the capacity to adapt to change as a central attribute of economic systems: ‘the economic problem of society is mainly one of rapid adaptation to changes in the particular circumstances of time and place’ (Hayek 1945, p. 524).

These ideas stimulated the emergence of an evolutionary theory of economic change in which the classical assumptions of long-run equilibrium were progressively abandoned (Alchian 1950; Nelson & Winter 1982; Boulding 1991; Nelson & Winter 2002). At the heart of this new theory was a recognition that the prediction of future changes is always imperfect, necessitating ‘trial-and-error’ or ‘search-oriented’ adaptations to novel conditions. Furthermore an analogue to Darwin’s model of speciation was proposed whereby firms and nations serve to generate, select and replicate innovations (Alchian 1950, p. 220).

Our understanding of the adaptive capacity of ecological systems is best attributed to the seminal work of Crawford Holling (1973). Based on evidence supporting the existence of multiple domains of attraction and non-linearity (Lewontin 1969), Holling asserted that mechanistic definitions of stability based on the existence of sustained states or general equilibria, though analytically tractable, are partial and often counterproductive. Holling instead proposed an alternative enabling attribute, which he termed ‘resilience’. He defined resilience as ‘a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables’ (Holling 1973, p. 14) and perhaps more specifically ‘the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist’ (Holling 1973, p. 17).

The resilience concept was then the subject of heated conceptual debate and modification, once again largely directed toward improved analytical tractability and empirical testability. For instance, Webster, Waide and Patten defined resilience as ‘the ability of an ecosystem to return to a reference state once displaced’ (Webster, Waide & Patten 1975, p. 1), Westman defined resilience as ‘the ability of a natural ecosystem to restore its structure following acute or chronic disturbance’ (Westman 1978, p. 705). Harrison defined resilience as ‘the response of the system to perturbations of the initial values of the state variables' (Harrison 1979, p. 660).

Many theoretical ecologists attempted to further confine the term. For instance, Don DeAngelis defined resilience as 'the speed with which a system returns to equilibrium state following a perturbation' (DeAngelis 1980, p. 764). Similarly Stuart Pimm defined resilience as 'how fast the variables return towards their equilibrium following a perturbation'. Pimm preferred to use the term 'stability' for the more general concept:

> A system is deemed stable if and only if the variables all return to the initial equilibrium following their being perturbed from it. A system is locally stable if this return is known to apply only certainly for small perturbations and globally stable if the system returns from all possible perturbations (Pimm 1984, p. 322).

Similarly Neubert and Caswell defined resilience as 'the rate at which perturbations to a stable ecological system decay' (1997).

However, as later highlighted by Holling (1996), in their efforts to enhance the analytical tractability and empirical testability of the concept, much of the original intent of the concept had been lost. That is, the concept was originally offered as a means of characterising the ability to dynamically adjust within a stability landscape comprising multiple domains of local equilibrium, rather than of characterising the capacity to rapidly return to a 'natural' reference state or general equilibrium. In response, Holling termed this new, more confined definition of resilience 'engineering resilience', while he termed his own multiple-equilibrium definition 'ecological resilience' (also see Justus 2008).

This synthesis is concerned with the more general, original ecological definition of resilience, broadly defined as the capacity of a system to adapt to shocks, shifts and perturbation while avoiding systemic failure.

3.4.3 Mechanisms underlying resilience

Functional mechanisms

The first apparent analysis of the functional basis for resilience in the economic discourse was contributed by George Stigler (1939). Together with the mechanism of 'divisibility' (discussed below), Stigler believed that 'adaptability' was a key mechanism for responding to shifting market conditions. He defined adaptability as the ability of a firm to adjust its output at a relatively low cost.

Albert Hart proposed a similar concept in his conception of 'flexibility'. He highlighted two important conditions for valuing flexibility: 'the anticipation of a change in anticipations' and 'the possibility of deferring decisions with or without special costs' (Hart 1942). He stressed that in the face of these conditions a fixed strategy is likely to be suboptimal and outlined the logic of a flexible approach as the explicit attention to maintaining contingent options pending future information.

Several later economists attempted to develop a more systematic definition of flexibility. Thomas Marschak and Richard Nelson (1962) defined flexibility as 'that characteristic of early decisions in a sequential chain which permits the decision-maker to adjust and take advantage of the information he receives as time elapses'. Robert Jones and Joseph Ostroy (1976) defined flexibility succinctly as 'having more future options available at lower cost', while David Upton defined flexibility more generally as 'the ability to change or react with little penalty in time, effort, cost or performance' (Upton 1994, p. 73).

The analytical basis for the mechanism emerged in the field of finance. In a seminal contribution to the field, Fisher Black and Myron Scholes (1973) derived a model for valuing 'European call options' – financial instruments representing future opportunities to buy securities at a given point in time. At its simplest the model was an expression of the contingent value of purchasing a stock at an agreed price. Although their model was constrained by a number of limiting assumptions, subsequent contributors significantly broadened the scope of options assessment (eg. Merton 1973; Boyle 1977; Cox, Ross & Rubinstein 1979), and extended the concepts so that they could be used to assess 'real' investment decisions – so-called real options analyses (Myers 1977; Brennan & Schwartz 1985; Dixit & Pindyck 1994; Smith & Nau 1995; Luehrman 1997, 1998b; Luehrman 1998a; Copeland & Antikarov 2001).

The important insight of real options theory was in valuing the benefits of a 'wait and see' approach. Instead of attempting to diversify against all possible shocks and shifts, in many cases it is more prudent to develop and maintain a suite of options. In doing so the system is capable of effectively responding to a larger range of future conditions at a lower cost than through diversification alone. Sophisticated investment strategies therefore combining their respective strengths of portfolio diversification and managerial flexibility, while reconciling potential tensions.

A similar mechanism has been observed in biological organisms in the concept of plasticity. The mechanism first emerged in biology from observations of the contingent expression of different developmental paths, or phenotypes, subject to a range of environmental conditions. Though originally treated as a curiosity, the mechanism was later recognised as fundamental to the persistence of organisms subject to changing environmental conditions (Baldwin 1896; Cowles 1911; Gause 1947; Klopfer & MacArthur 1960; Bradshaw 1965; Morse 1971; Baker 1974; Via & Lande 1985; Greenberg 1990; Scheiner 1993; Via et al. 1995; Walbot 1996; DeWitt & Scheiner 2004; Pigliucci 2005). Furthermore, a tension was identified between the range and fitness of the conditional response function or 'reaction norm' (Woltereck 1909; Schmalhausen 1949) and the energy and material costs of sustaining that flexibility (DeWitt, Sih & Wilson 1998).

Biological plasticity research therefore demonstrated that tensions can also arise between functional intensity and managerial flexibility, necessitating a nuanced reconciliation of the two strategies.

The mechanism of contingent expression of alternative states was also recognised to occur in biological communities. In addition to reducing the sensitivity of ecological communities to disturbances at a point in time, Holling (1973) suggested that minor, seemingly redundant species could also fulfil an important role as contingent options subject to shocks and shifts in conditions. Specifically, Holling observed that following significant perturbations of biological communities many seemingly redundant species were able to expand their role by colonising new niche spaces and increasing their numbers. Far from a sign of weakness in a biological community, Holling understood that these adjustments assist the community as a whole with persisting despite partial destruction of key populations.

Thus, both the economic and ecological discourses recognised the advantage of maintaining contingent functional responses subject to shifting exogenous and endogenous conditions. Consistent with the terminology applied in economics, this mechanism will be termed 'functional flexibility'.

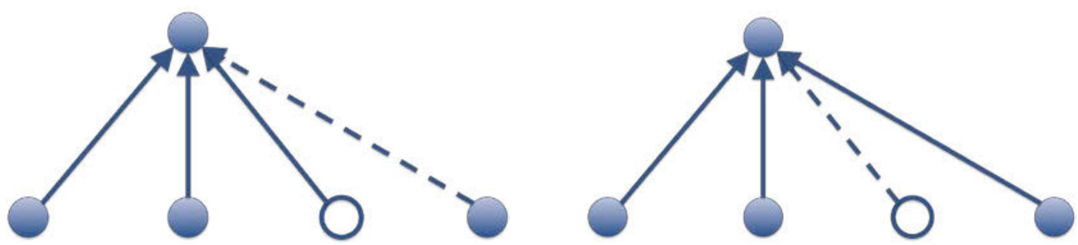

Figure 5 - Systems diagram of the functional flexibility mechanism

Figure 5 provides a systems diagram of the functional flexibility mechanism. The component survives by adjusting its resource source in response to partial failure.

Structural mechanisms

George Stigler (1939) also appears to provide the first structural basis for the relative performance of firms subject to shifts in market conditions. Stigler proposed 'divisibility' of plant as a key enabling characteristic, which he characterised as the presence of a large number of small components that could be partially applied to generate variable levels of production.

The concept was significantly developed by the economist Herbert Simon in his now famous analysis of the adaptive capacity of systems (Simon 1962). Simon identified all living systems as 'nearly decomposable' into assemblies of loosely interdependent, semi-autonomous components. Simon identified this ability as a critical mechanism for withstanding and effectively adapting to the partial destruction of a continually shifting environment.

The theory later re-emerged with the disintegration of vertically integrated firms into so-called 'dynamic networks' or 'boundaryless organisations' (Miles & Snow 1986; Achrol 1991; Snow, Miles & Coleman Jr 1992; Daft & Lewin 1993; Ashkenas et al. 1995; Miles & Snow 1996). Citing several examples of industries subject to intense technological change, several economists and management theorists observed a general trend from highly vertically integrated firms toward industries comprising multiple economically interdependent yet organisationally independent firms. This new organisational form was interpreted as being a means of effectively adapting to a rapidly evolving environment – a claim that was the subject of considerable conjecture (Williamson 1985, 1991; Langlois 1992).

Subsequent theorists added nuance to the mechanism under the broad concept of 'interfirm modularity' (Sanchez & Mahoney 1996; Schilling 2000; Langlois 2002). Rather than prescribing a specific organisational form, these theorists recognised that modularity may manifest in both vertically integrated and disaggregated organisational forms. Of greater importance is how the structures of firms are able to maintain efficient material, financial and informational linkages and cross-functional support structures while simultaneously maintaining sufficient autonomy and separability among the organisations' functions to nurture creativity and isolate failure.

The first evidence of the structural basis for resilience in ecology may be found in Holling's original analysis (Holling 1973). Holling characterised ecosystems as a 'spatial mosaic' comprising a heterogenous mix of loosely connected communities. He observed that the loosely connected nature of communities serves to provide niches for a wider range of species than would otherwise occur with stronger levels of cross-exchange. Furthermore he observed that species will often only expand their territory during significant periods of shocks or shifts. Rather than being a source of instability, Holling observed this structure as an ideal ecosystem-level adaptation to shocks and shifts in conditions, as the loosely connected regions serve to foster a wider range of species pending a change in conditions.

A similar concept has also been recognised as a mechanism employed by biological organisms and communities in their responses to highly variable environments (White 1979; Harper 1981; Watkinson & White 1986; Hall & Hughes 1996; Marfenin 1997; Schlosser & Wagner 2004; de Kroon et al. 2005; Kashtan et al. 2009). Though particularly evident in immobile organisms and communities subject to high variability in environmental conditions, the presence of varying degrees of modular assembly have been observed in genetic biology, developmental biology, and evolutionary biology (see Schlosser & Wagner 2004).

Reflecting Simon's earlier theory, biologists have theorised two related advantages of this modular form: *survivability*, owing to the ability to persist despite the partial destruction often involved in perturbation; and *evolvability*, owing to the ability to limit interference between the adaptation of different functions (Wagner & Altenberg 1996; Lipson, Pollack & Suh 2002).

The basis for modularity was significantly extended by the advancement of panarchy theory (Gunderson & Holling 2002). Panarchy theory describes the adaptive evolution of living systems as a continual adaptive cycle of growth, accumulation, restructuring and renewal. The adaptive cycle occur across spatial and temporal scales, mediated through cross-scale interactions: a sub-system can 'revolt' by developing new structures or behaviours, but also 'remember' by drawing structures or behaviours from elsewhere in the system. The separation of systems into semi-autonomous components was therefore identified to represent an important structural basis for reconciling persistence and change, as each component provides a 'memory' of structures and systems for the system to draw on if circumstances change.

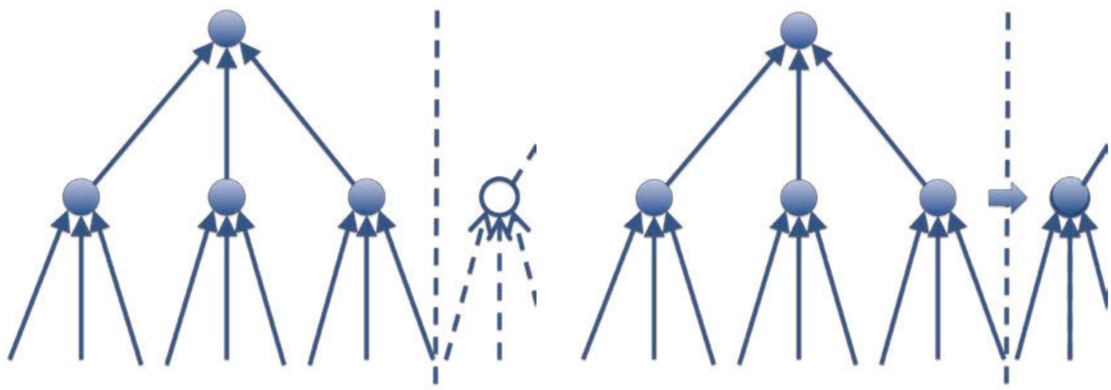

Figure 6 - Systems diagram of the structural modularity mechanism

Figure 6 provides a systems diagram of the structural modularity mechanism. The semi-permeable module boundary (shown dotted) restricts cascading failure and systemic destruction (left) while supporting the development of and permitting the flow of innovation (right).

In summary, the resilience of a system to surprise shocks and shifts may be described as emerging from a duality of mechanisms: the development of contingent functional components with different responses to the suite of possible perturbations (here termed 'functional flexibility'), and the assembly of systems comprising semi-autonomous, separable and combinable modules (here termed 'structural modularity).

3.5 Synthesis: a conceptual framework for describing systemic performance

The review above provides a synthesis of how, since their earliest days, the disciplines of economics and ecology have sought to grapple with notions of systemic performance. From this unique perspective the synthesis has been able to draw new connections and identify shared patterns across both disciplines – providing an opportunity to develop a formidable new conceptual framework. This section provides an overview of the key features of that conceptual framework, makes an argument for its novelty and insight on the basis of a comparison to similar works.

3.5.1 Overview of the framework

This review has identified that the performance of an ecological and economic system arises from the alignment of three attributes:

- the capacity of a system to thrive despite resource scarcity and competition (i.e. 'ascendance')
- the capacity of a system to absorb variability, fluctuation and disturbance while remaining essentially unchanged (i.e. 'resistance')
- the capacity of a system to adapt to shocks, shifts and perturbation while avoiding systemic failure (i.e. 'resilience').

Furthermore each of these attributes has been observed to arise from the alignment of a duality of functional and structural mechanisms. That is,

- *Ascendance* was observed to arise from the differentiation of intensive functional components (i.e. 'functional intensity') and the connection of functional components to form extensive, synergistic assemblies (i.e. 'structural integrity').
- *Resistance* was observed to arise from the development of functional components with different sensitivities to the suite of probable disturbances (i.e. 'functional diversity') and from the assembly of functional components within complex, nested networks capable of effecting compensatory negative feedback (i.e. 'structural complexity').
- *Resilience* was observed to arise from the development of contingent functional activities with different responses to the suite of possible perturbations (i.e. 'functional flexibility') and the assembly of systems comprising semi-autonomous, separable and combinable functional components (i.e. 'structural modularity').

The attributes and mechanisms may therefore be depicted as a series of overlapping attributes and mechanisms for achieving systemic performance, as shown in Figure 7 below.

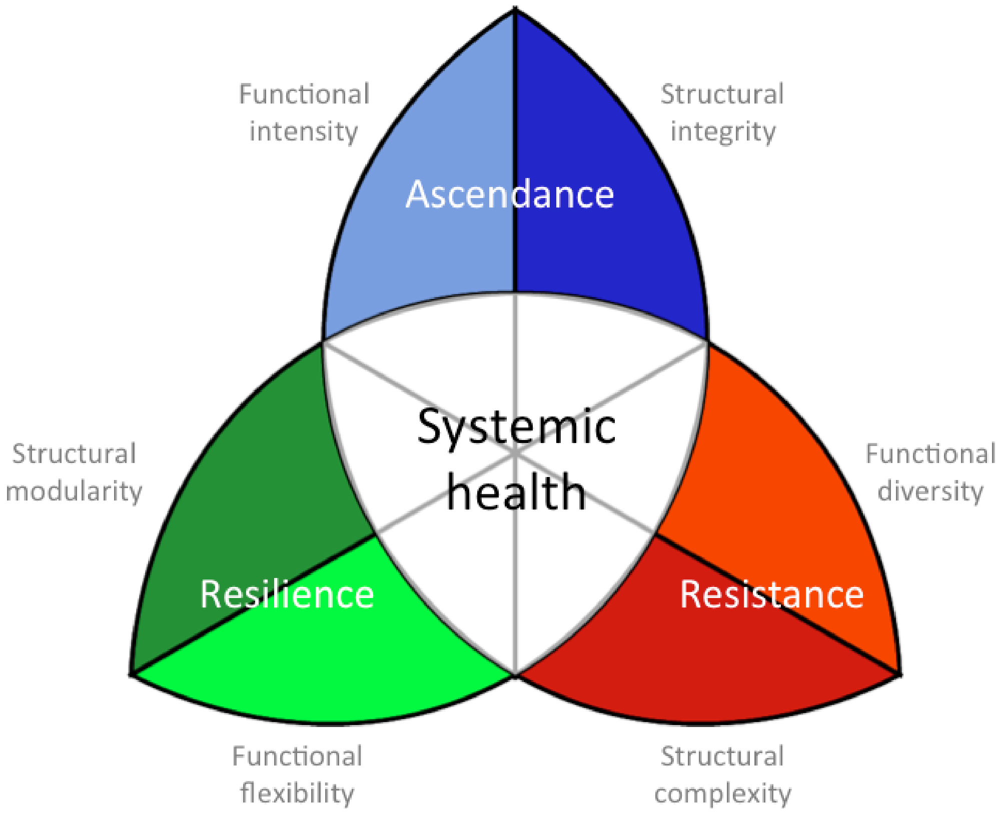

Figure 7 – Overlapping diagram representation of the relationship between key systemic performance concepts

This 'overlapping' model indicates that each of the attributes and mechanisms must be expressed to varying degrees within each system while simultaneously highlighting the potential tensions between the attributes and mechanisms. For example, studies of savannah grazing, forest fires and other managed ecosystem disturbances have demonstrated that exclusive attention to productivity or reliability can lead to brittle systems when exposed to shocks and shifts in conditions (Holling 1973; Walker et al. 1981; Holling 1986). A similar tension has been observed in economic systems where the increasingly integrated and complex global financial market has been found to be increasingly vulnerable to systemic risk and cascading failure, as occurred during the global financial crisis (Goldin & Vogel 2010).

However, it is also important to emphasise that the expression of the attributes is much more than a 'trade-off' or zero sum game. Indeed the three attributes may be alternatively expressed as an alignment of nested properties as in Figure 8 below.

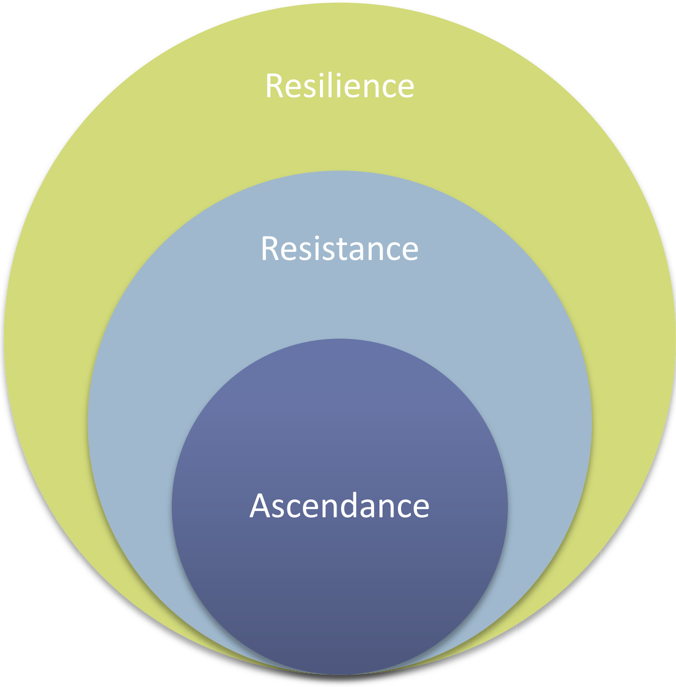

Figure 8 – Hierarchy diagram representation of the attributes of systemic performance

That is, resistance may be expressed as an extension or modification of ascendance for situations where the driving variables of the system are subject to variability and fluctuation, while resilience may be expressed as an extension or modification of resistance where the state variables of the system are also inevitably the subject of change owing to shocks and shifts in conditions.

This explains some of the controversy in the discourse, particularly with respect to the definition of resilience (Klein, Nicholls & Thomalla 2003), which is sometimes used to imply the more specific attributes of adapting to surprise shocks and shifts, and sometimes used to imply a comprehensive suite of attributes, including the ecological concept of resistance (Walker et al. 2004).

A similar case may be made for the alignment of the mechanisms as shown in Figure 9 below.

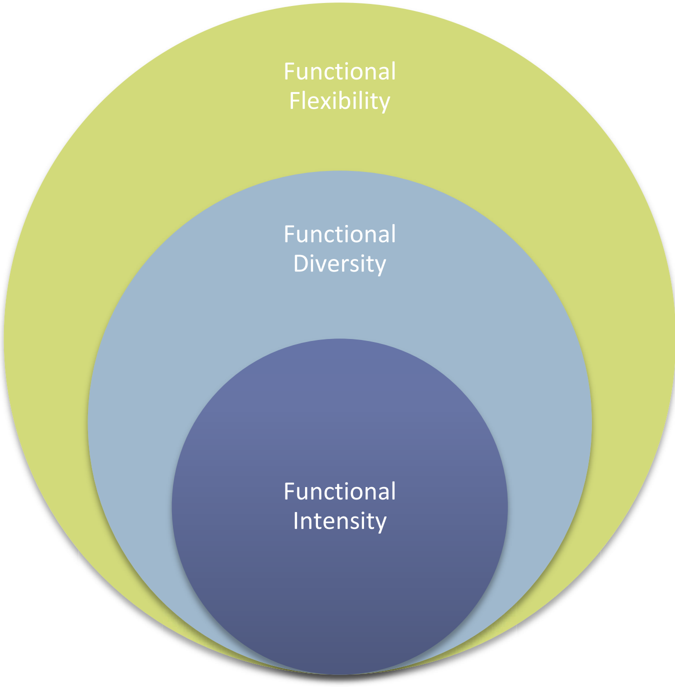

Figure 9 – Hierarchy diagram representation of the functional mechanisms of systemic performance

Each functional mechanism may be understood as extending and including its 'lower level' mechanisms. While functional intensity may be understood as the progressive differentiation and selection of components subject to a given set of conditions, functional diversity may be understood as a form of 'meta intensity' whereby the system adjusts to best respond to the fluctuations experienced by the system across time and space. Similarly, functional flexibility may be understood as a form of 'meta diversity' whereby components that offer limited diversification benefits at a given point in time and space represent contingent development pathways of the system subject to a change in conditions.

Studies of grassland ecosystems provide a clear illustration of the nesting of functional attributes. These ecosystems have been shown to favour specialised rapidly growing grasses, at least at a given location during periods of abundant rainfall (i.e. they promote *functional intensity*). However across a broader region and time span, the same system could be said to favour both rapidly growing and drought-tolerant grasses so the ecosystem can persist across the drought cycle (i.e. *functional diversity*). When this same ecosystem is exposed to a new fire regime, a normally dormant or invasive species may grow in dominance, shift the balance of the ecosystem and, despite causing a loss of function in the short term, ultimately lead to a better-adapted ecosystem (i.e. demonstrating *functional flexibility*).

This alignment of the functional mechanisms is also illustrated in the review of modern financial theory. For instance, Markowitz's theory of the financial portfolio demonstrated that diversifying an investment portfolio (i.e. adding functional diversity) can simultaneously increase yield and reduce investment volatility when implemented effectively. Similarly, real options theory demonstrates that holding a well-designed mix of contingent investment options (i.e. adding functional flexibility) can simultaneously increase the long term return while reducing the exposure of the investor to catastrophic risk.

Intimate and complex connections may also be identified between the structural mechanisms as shown in Figure 10.

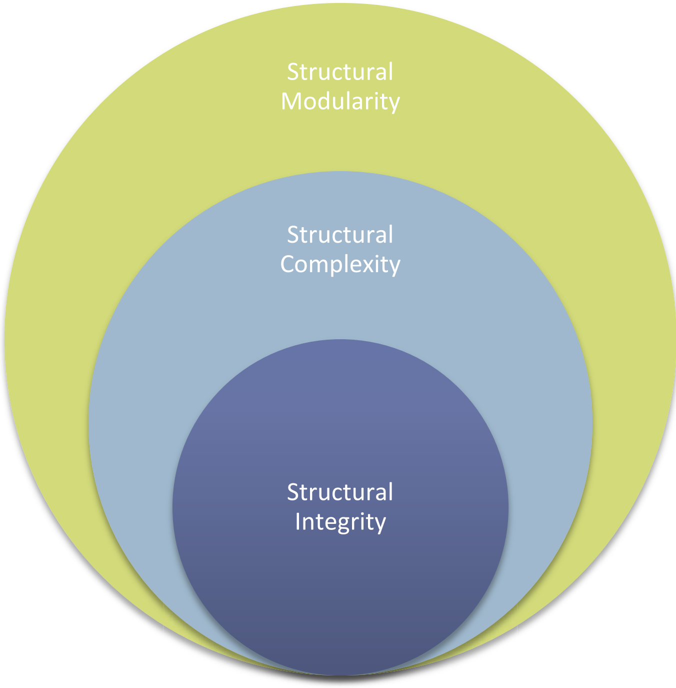

Figure 10 – Hierarchy diagram representation of the structural mechanisms of systemic performance

As identified in the literature review, structural integrity alone may offer strong network synergies, but unless those connections are uniquely coupled to the fluctuations experienced by the system they will be inherently unstable – necessitating a degree of structural complexity. The review has also highlighted that structural complexity alone can prove quite brittle when subjected to partial failures and shifts in conditions, necessitating the emergence of separable yet combinable linkages and assemblies, giving rise to a degree of structural modularity.

For example, consider the case of a complex forest ecosystem. A forest ecosystem has an incredible number of exchanges of energy and nutrients as detritus is broken down to provide nutrition for plants, which then provide foliage for insects, which then provide food for animals and so forth (that is, the ecosystem is *structurally integrated*). These tight energy and resource linkages lead to an incredible level of efficiency and conservancy. However, the linkages are non-random and highly nested (that is, they are *structurally complex*). This means if one species experiences a die-off owing to temporarily undesirable conditions, its predators will preferentially target its rival species, providing a degree of regulation to variability and fluctuation. Furthermore, the forest is also much more than a nested 'tree' but rather a mosaic of forest patches with permeable but identifiable boundaries (i.e. it has *structural modularity*). This means that if a forest patch experiences a shock or shift, such as an invasive species, then neighbouring forest patches will be partially shielded from that invasion.

This reconciliation of the structural mechanisms is also illustrated in the review of inter-firm modularity theory (Sanchez & Mahoney 1996; Schilling 2000; Langlois 2002). The most effective organisations were observed to align their competing requirements to facilitate efficient material, financial and informational linkages and synergies among divisions (i.e. *structural integrity*), provide adequate cross-division support to withstand market volatility (i.e. *structural complexity*) and sufficient divisional autonomy to facilitate intra-firm innovation and avoid cascading failure (i.e. *structural modularity*).

However, both the 'overlap' and the 'hierarchy' are partial metaphors for the complex reconciliation of the attributes and mechanisms required in each unique situation.

3.5.2 Comparison with similar conceptual frameworks

The earliest evidence of a similar conceptual framework to that presented here may be found in the work of David Frey (1975). In seeking to describe the biological integrity of aquatic ecosystems, Frey described a series of necessary conditions: the capacity to direct and conserve sufficient energy and nutrient flows to develop and maintain the ecosystem's functions and structures; the capacity 'to accommodate and recover from such short-term natural stresses as scouring flushouts in rivers, episodes of volcanism, landslides, and so forth'; and the capacity 'to adjust to long-term changes in climate, vegetation, soil development, and internal trends within the system itself'. The parallels with the proposed framework are clear, with the above three attributes broadly aligning with the top-level concepts of ascendance, resistance and resilience, respectively. However, as may be observed in the language used by Frey, the definitions were targeted at a relatively confined set of systems and no attempt was made to further unpack the underlying mechanisms.

Another example may be found in John Philip Grime's theory of plant strategies (1977). Grime proposed that all plants employ a combination of three primary strategies:

‘competitive’, ‘stress-tolerant’, and ‘ruderal’ strategies. According to Grime, each strategy may be understood as an extreme in a matrix of stress, where stress is defined as ‘conditions that restrict production e.g., shortages of light, water, or mineral nutrients and suboptimal temperatures’ (Grime 1977, p. 1), and disturbance, defined as ‘the partial or total destruction of the plant biomass from the action activities of herbivores, pathogens, man (trampling, mowing and ploughing), and from phenomena such as wind damage, frosts, dessication, soil erosion, and fire’ (Grime 1977, p. 1). Grime placed the three strategies in a triangle to illustrate the nuance and tension between the strategies he identified.

There are clear parallels with the framework described here, with competitive, stress-tolerant, and ruderal strategies roughly corresponding to more specific forms of ascendance, resistance and resilience attributes, respectively. However, largely owing to their specific purpose and scope, the definitions, attributes and mechanisms do not provide sufficient generality as a conceptual framework for understanding the performance of economic or ecological systems.

Another framework presented in the literature that is similar to the one described here may be found in the ‘ecosystem health’ framework proposed by Robert Costanza (1992). Costanza defined ecosystem health as comprising three attributes: ‘vigor’, defined as the function, productivity or throughput of a system; ‘organisation’, defined as the structure and diversity of a system; and ‘resilience’, defined as the ability to recover from stress. Accordingly, the ecosystem health could be quantified by combining measures of the three identified attributes. For example, biological throughput, biodiversity and the scope for growth could be applied as measures of vigor, organisation and resilience, respectively, and their combination applied as a measure of ecosystem health.

Once again clear parallels may be observed between Costanza’s framework and that proposed here, however several clear distinctions remain. Whereas Costanza proposes vigour and organisation as attributes, the framework proposed here accommodates those concepts as constituent mechanisms (roughly aligning with functional intensity and structural complexity respectively). In making this distinction several additional constituent mechanisms have been suggested (e.g. structural integrity, functional diversity, functional flexibility, structural modularity), potentially providing a richer language of conceptual distinctions. Furthermore, as distinct from the ecosystem health framework, the attributes in the systemic performance framework identified here are each motivated by a specific driver, providing a basis to assess the relative importance of the attributes for specific situations.

A recent translation of resilience theory to the field of regional economics and economic geography provides the most recent similar contribution (Martin & Sunley 2014). Ron Martin and Peter Sunley identify five aspects or dimensions of economic regional resilience: vulnerability (the sensitivity or propensity of a region's firms and workers to different types of shock; shocks (the origin, nature and incidence of a disturbance, and the scale, nature and duration thereof), resistance (the initial impact of the shock on a region's economy); robustness (how a region's firms, workers and institutions adjust and adapt to shocks, including the role of external mechanisms, and public interventions and support structures); and recoverability (the extent and nature of recovery of the region's economy from shocks, and the nature of the path to which the region recovers). They also identify several constituent mechanisms: structural diversity, which in this instance implies industrial diversity; modularity or the degree to which sectoral or organizational components are separable or weakly interlinked; structural redundancy, which implies the extent to which certain sectors or firms can substitute for one another if some fail, and by the extent to which resources can be put to related or alternative uses; and the 'rivet effect', which refers to the benefits of having redundant industries pending a collapse in a given industry.

This is the most similar identified conceptual framework to that proposed in this synthesis. Similar to the proposed framework, Sunley and Martin have identified a set of dimensions or attributes, however the selected dimensions differ. Features such as vulnerability and robustness are conceptually interladen with the concepts of resistance and resilience and their 'marginal benefit' or incremental contribution is unclear. The synthesis presented in this chapter suggests that the concept of robustness is largely a combination of resistance and resilience as identified in this thesis. However, as is discussed above, conflating resistance and resilience can lead to considerable conceptual pitfalls owing to tensions that may arise between the attributes. Vulnerability largely represents the inverse of robustness, and therefore poses the same conceptual pitfalls.

Also similar to the proposed framework, Sunley and Martin have identified a set of supporting mechanisms. 'Structural diversity' broadly aligns with functional diversity as identified in this thesis, 'modularity' corresponds directly with structural modularity, 'structural redundancy' is very similar in definition to functional flexibility in this thesis, while the rivet effect broadly corresponds to a combination of the functional diversity and flexibility mechanisms. Critically, no attempt is made in the regional economic resilience framework to link specific mechanisms to specific dimensions or attributes, which as discussed above can lead to important potential tensions between attributes being missed.

Finally, the regional economic resilience framework does not integrate or explicitly analyse the concepts surrounding precluding resource competition (i.e. 'ascendance' and its mechanisms as outlined in this synthesis). The discussion does refer at several points to 'specialisation', which is similar to the concept of functional vitality. However, as discussed above, the tension between specialisation and the other concepts including diversity and redundancy is not explicitly analysed. The paper also refers to the concept of economic competitiveness at several points, which is similar in some respects to the concept of ascendance, however the tensions or alignments between competitiveness and resilience are not explicitly analysed.

3.6 Discussion

3.6.1 Contributions

A key strength of the framework is in providing a more comprehensive conceptual model for the attributes and mechanisms underlying the performance of economic and ecological systems. As emphasised in the review above, a significant volume of research has been conducted to explore specific attributes or mechanisms, but there has been a limited number of studies seeking to integrate the concepts into a coherent framework. Furthermore the reviewed conceptual frameworks that attempt to integrate the concepts have focussed on a more confined scope of biological or ecological systems as discussed above.

Secondly, the framework extends the strengths of Grime's framework in motivating the attributes by specific drivers. In so doing the framework offers a means by which to assess the role and relative importance of each attribute and mechanism for specific situations.

Finally, the framework builds on the strengths of Costanza's ecosystem health framework and Martin and Sunley's regional economic resilience framework in seeking to identify and elaborate specific mechanisms. However as distinct from these frameworks, the synthesis directly links specific attributes of performance to specific mechanisms. In so doing the framework offers a conceptual tool for analysing and guiding ecological and economic systems for improved systemic performance.

For instance, in situations driven by competition for a constrained and shared resource base, the mechanisms of functional intensity and structural integrity are likely to be a significant focus. For situations characterised by high levels of variability, fluctuation and disturbance, the mechanisms of functional diversity and structural complexity are likely to be important.

And for situations driven by surprise shocks, shifts and perturbation, the mechanisms of functional flexibility and structural modularity are likely to be of concern.

3.6.2 Limitations

The framework synthesises a broad range of ecological and economic literature and in doing so it has been necessary to confine the scope of the synthesis in several respects.

Firstly, by seeking to identify general attributes that span both disciplines, the framework has excluded many specifics. For example, the framework provides little guidance on the specific sources of plant health or disturbance, as in Philip Grime's conceptual framework of plant strategies – or the specific drivers and mechanisms underlying aquatic ecosystem health, as in David Frey's framework. Though a degree of specificity of guidance is necessarily lost in driving towards a framework of this generality, it is clear that further work will be required to translate the conceptual framework to specific problem contexts.

However, perhaps a much more significant limitation of the framework is the exclusion of the higher social dimensions of power, conflict, equality and justice. In excluding these higher dimensions, the framework provides a necessary but partial characterisation of a socially desirable economic outcome.

3.7 Conclusions

The review of economic and ecological literature presented in this chapter has revealed a remarkably consistent set of concepts for describing systemic performance from both disciplines. The unique historical and interdisciplinary perspective offered by this review has also enabled new connections to be drawn that have been distilled into a novel conceptual framework. The framework is proposed as an insightful 'thinking tool' for describing and analysing systemic performance in new ways while potentially stimulating new strategies for designing our cities.

The next logical step is to translate this framework into the domain of concern of this thesis – urban water and energy systems – and to connect the concepts elaborated in this framework with the analytical methods available for assessing them.

The following chapters seek to provide the first steps in that direction.

4 Translations: exploring the relevance and implications of the concepts to urban water and energy systems

4.1 Introduction

The conceptual framework identified in the preceding chapter offer the prospect of providing an improved means for conceptualising systemic performance. But how do the frameworks translate to our cities, and what new insights might they reveal?

This chapter explores the implications of the conceptual framework for urban systems with a specific focus on urban water and energy systems. The chapter begins by analysing each of the guiding attributes identified within the framework and compares each with existing benchmarks of performance in energy and water systems. In so doing, the chapter reveals how these attributes provide an improved conceptual model. The mechanisms underlying each attribute are explored in turn, with a focus on identifying planning and design approaches for improving systemic performance, highlighting where possible case studies that demonstrate their tangible benefits. A discussion follows reviewing the key contributions of the framework relative to existing practice.

The chapter begins by exploring the concept of ascendance and its implications for urban water and energy systems.

4.2 Ascendance: performance subject to scarcity and competition

Though urban water and energy utilities are often partially shielded from resource scarcity and competition by monopoly conditions or regulatory controls, scarcity and competition are critical drivers in system planning and design owing to the principle of opportunity cost. That is, any given investment of resources will be associated with a suite of foregone alternative investments, both in physical and financial resources.

‘Ascendance’, or the capacity of a system to thrive despite resource scarcity and competition, could therefore have considerable relevance to urban water and energy systems.

In the context of urban water and energy planning, the attribute of ascendance emphasises the importance of managing the resource throughput of systems and is closely associated with conventionally applied performance indicators including efficiency, cost-effectiveness and productivity.

However, as distinct from conventional notions of efficiency and productivity, ascendance provides a 'systemic' or multi-scale perspective of performance. That is, ascendance theory recognises that all systems represent a constituent component of a set of nested ecological and economic systems to which they contribute, and on which they depend. Furthermore, resource flows directed to these supporting systems or 'tributes' are recognised as essential to sustaining their ongoing performance (Ulanowicz 1997).

From an ecological perspective, ascendance provides the basis for analysing the physical performance of urban water and energy systems from multiple scales, including the system's role and impact on ecosystems. Taking a systemic perspective, urban water and energy systems represent a sub-component of the ecosystems in which they are embedded. As such, any development of urban water and energy systems that undermines the performance of those ecosystems is counterproductive from the systemic perspective of ascendance theory.

The proposed systemic performance attribute of 'ascendance' therefore provides an integrated framework for reconciling the potentially competing goals of improving the performance of the system while remaining within tolerable ecological thresholds including the preservation of environmental flows and management of pollutant loads to maintain ecosystem health.

From an economic perspective, ascendance provides a basis for analysing the economic performance of water and energy systems from a range of cost perspectives. Since an urban water or energy utility is ultimately dependent on the healthy functioning of its supporting economy, strategic plans should ideally be optimised from the cost perspective of society as a whole rather than the cost perspective of the utility alone.

The hierarchical conception of ascendance similarly highlights that the performance of an energy or water system can only be sustained if its key economic components (i.e. customers, institutions and other key partners) are financially viable.

For example, programs to incentivise rainwater tanks and PV solar on roofs can shift the financial burden from water and energy utilities to individual customers. It is therefore important for the economic analysis to account for the financial costs borne by both customers and utilities. Furthermore, a distribution analysis should be undertaken to ensure customers are sufficiently compensated for their contribution to the network through rebates or other incentives.

Inversely, appliance efficiency programs undertaken by utilities can provide significant benefits to households in energy and water bill savings. A distribution analysis should ideally be undertaken to ensure utilities are appropriately incentivised for such programs through rate adjustments or other transfer payments.

While the practice of undertaking both societal economic analysis and stakeholder distribution analysis is increasingly advocated as best practice by authorities (e.g. USEPA 2010), ascendance provides a coherent conceptual framework for such a multi-scale perspective beyond equity concerns alone.

The analysis will now turn to the two mechanisms which have been identified as underlying the ascendance of systems subject to resource scarcity and competition: functional intensity and structural integrity.

4.2.1 Functional intensity

As elaborated in Chapter 3, functional intensity implies the identification and maintenance of activities that most effectively apply the available resources to maximum effect by one of three processes: resources that were previously unavailable to the system may be exploited, existing resource flows may be more efficiently applied, or waste resources may be captured and recirculated.

The mechanism therefore has significant relevance in the context of water systems, where emerging constraints on existing water resources have revealed that alongside capacity augmentations there are cost-effective opportunities for service efficiency and recycling. Simple measures such as low flow rate showerheads have been shown to provide a similar service with lower physical and financial costs. Similarly, stormwater and wastewater recycling processes that recirculate resources are increasingly considered a viable alternative to conventional supply augmentations.

The mechanism of functional intensity also has significant relevance in energy systems where significant opportunities have been revealed for ‘negawatts’ or avoided supply and network capacity through energy efficiency and demand management measures (Lovins 1992). Significant opportunities also exist for ‘recirculation’ where normally the wasted heat of power generation may be used for heating (in cogeneration systems) and for both heating and cooling (in trigeneration systems) (Tchouate Héteu 2001).

Analytically, the mechanism of functional intensity highlights the value of building ‘competition’ among a broad suite of options in terms of their physical and economic efficiency and intensity. The 'economic intensity' of alternative options is typically assessed through a variety of methods including cost-benefit analysis and cost-effectiveness analysis, and, though still less commonly applied, the 'ecological intensity' or physical resource efficiency and impact of alternative systems may also be assessed by a wide range of methods, potentially including material flow analysis, material input per unit service analysis, ecological footprint analysis and life cycle analysis.

The mechanism also highlights the value of so-called 'end-use analysis' methods (White, Milne & Riedy 2004). As distinct from the more traditional statistical regression analysis approaches for analysing and forecasting demand, end-use analysis methods estimate current and future demands from the 'bottom up' in terms of the activities or 'end uses' that comprise demand (e.g. showering, cooling, clothes washing etc.). In so doing, end-use analysis provides a useful method for developing plausible and internally consistent demand scenarios while simultaneously revealing the potential for end-use efficiency, service efficiency and substitution potentials.

4.2.2 Structural integrity

Structural integrity implies the efficient linkage of functional components to simultaneously maximise network synergies and minimise network costs and other tensions between components.

In the context of urban water and energy systems design, the mechanism draws attention to the role of transmission and distribution networks in facilitating network efficiencies, including economies of scale and agglomeration (Yatchew 2000).

The mechanism also draws attention to the resource efficiency of alternative network topologies and designs. At its most basic level, this involves optimising the layout, design and operation of network components to minimise costs where possible. In the absence of significant fluctuations in demand or capacity and the associated challenges of maintaining reliability, this process typically leads to a branched network configuration with minimal topological or capacity redundancy (Swamee & Sharma 2008).

4.2.3 Designing for ascendance

While the review above highlights the application of both functional intensity and structural integrity in urban water and energy systems design to varying degrees, the conceptual framework suggests that the full benefits of the mechanisms will only be realised when they are aligned into an integrated design of both 'function' and 'structure'.

In the case of urban water and energy systems design this implies designing individual system components in the context of their consequent impacts on overall system-wide resource efficiency. For instance, although there are typically economies of scale associated with individual components (e.g. generators, wastewater treatment plants), diseconomies can also occur chiefly owing to the costs associated with transmitting energy, water and wastewater across increasingly extensive networks.

The conceptual framework therefore highlights the synergies and tensions that can arise when one adopts a systemic or holistic perspective, and the strengths of considering a broader suite of system configurations, including embedded or decentralised infrastructure systems.

For instance, by locating water supply and treatment closer to the consumer, a decentralised water system can minimise the transmission of water across the network, potentially resulting in significant system-wide capital and operational savings (Pinkham et al. 2004).

A similar effect has been observed in energy networks. So-called embedded generation assets dispersed across the distribution network can dramatically reduce the burden on feeder and transmission infrastructure, leading to deferred or avoided capacity augmentations and reduced operational costs (Jenkins 1995; Jenkins et al. 2000).

A clear demonstration of the benefits of such an approach within the water sector is offered by a case study seeking to identify the optimum configuration of a wastewater network (Clark 1997). Several alternative treatment plant scales and configurations were tested within idealised network designs to explore the overall cost, including both treatment and network components. The study revealed that an equilibrium point occurred beyond which the economies of scale associated with wastewater treatment plants were overwhelmed by diseconomies associated with the increasingly extensive wastewater collection networks needed to serve them, leading to a unique ‘optimal scale’ for a given situation. This ‘optimal scale’ was affected by several key factors including treatment plant cost, network cost, and equivalent population density.

Although integrated analyses such as these remain largely within the preserve of academia, they demonstrate the possible synergies and tensions that arise between the selection of specific components such as energy generators and water treatment plants and their corresponding network infrastructures, and the benefits of taking a holistic perspective of system performance.

The limitation of ascendance as an exclusive frame of reference is its focus on relatively unchanging conditions. Situations involving significant variability, fluctuation, shocks and shifts warrant consideration of additional attributes of performance. These are detailed below.

4.3 Resistance: performance subject to variability and fluctuation

Almost all urban water systems are exposed to some degree of variability and fluctuation: water consumption and wastewater flows fluctuate as residents and businesses carry out their daily activities; wastewater and stormwater inflows vary with rainfall events; and surface and groundwater source flows and storages fluctuate with daily, seasonal and interannual weather variability.

Similarly, all energy systems are exposed to variability and fluctuation in some form: peak energy loads fluctuate owing to fluctuations in heating and cooling demand and other activities, and generation fluctuates owing to facility down times, wind variation, solar insolation and other periodic fluctuations.

'Resistance' or the ability of a system to absorb this variability and fluctuation while remaining essentially unaffected is evidently of interest to urban water and energy planners and designers.

In the context of urban water and energy systems, a focus on the attribute of resistance highlights the importance of managing the sensitivity or stability of systems and is closely associated with the conventional performance indicators of reliability and risk management.

However, as distinct from conventional reliability measures the attribute of resistance focuses on systemic performance rather than the operational reliability of components. In so doing, emergent or systemic interactions among components can be effectively managed and exploited as detailed below.

Another key distinguishing feature of systemic resistance is its explicit framing as a response to variability and fluctuation. Conventional risk and reliability measures conflate disturbances that may be feasibly anticipated and planned for (here termed variability and fluctuation) with disturbances that are inherently surprising (here termed shocks and shifts). This conflation can lead to an undue emphasis on local stability at the expense of systemic vulnerability to shocks and shifts. As summarised in the previous chapter there is a significant body of ecological research that suggests that undue emphasis on minimising variability and fluctuations (i.e. 'local stability') can counter-intuitively degrade the performance of systems exposed to surprise shocks and shifts (i.e. 'global stability'). As such there are clear advantages to analysing and managing variability or fluctuation and shocks or shifts concurrently but distinctly.

The conceptual framework outlined in Chapter 3 identified two mechanisms underlying systemic resistance: functional diversity and structural complexity.

4.3.1 Functional diversity

The mechanism of functional diversity implies the development of components with different sensitivities to the suite of probable disturbances and emphasises a range of processes including 'resource diversification', 'spatial diversification' and 'temporal diversification'.

In the context of water systems the mechanism of resource diversity highlights the value of developing and maintaining a suite of qualitatively different water resources including surface water, recycled wastewater and desalinated seawater where available.

It also highlights the value of developing and maintaining water resources with different spatial domains or 'patches', which in the context of urban water systems implies catchments subject to differing hydrological regimes. This effect is quite pronounced in coastal cities whose inland catchments are subjected to a qualitatively different rainfall regime to more coastal catchments. For such situations, a 'spatially diverse' water resource portfolio comprising a mix of catchment regions will likely offer improved systemic performance.

The mechanism also highlights the benefits of water resources with differing temporal domains or 'rhythms', which in the context of urban water systems implicates catchments with differing catchment response times. For instance, while a reservoir requires a significant rainfall event to generate appreciable runoff, stormwater and rainwater harvesting systems can exploit shorter and more frequent rainfall events (Coombes & Barry 2008). A 'temporally diverse' water resource portfolio can therefore exploit a broader suite of rainfall events and thereby confer improved systemic performance subject to a variable climate.

A similar set of observations may be made regarding energy generation portfolios. For instance, concentrated energy resource portfolios sensitive to a specific fluctuation (e.g. gas-fired generators sensitive to international gas price fluctuations) may focus on developing and maintaining generation assets with categorically different risk profiles (e.g. renewables) (Awerbuch 2006).

Similarly, while spatial and temporal diversification has not featured as prominently in energy systems theory historically, it has been the subject of significant interest in recent years with the rise of high-penetration renewable systems. For instance, energy portfolios that draw from a geographically dispersed set of wind turbines will typically outperform a cluster of generators in a limited geographical region (Grothe & Schnieders 2011). Similarly, the old language of 'baseload' and 'peaking' generation assets is increasingly being abandoned for a richer conception of temporal diversity based around a designed mix of 'variable' generation assets (Ela & O'Malley 2012).

Analytically, functional diversity draws attention to the potential value of analysing and ideally exploiting the covariance in the reliability of infrastructure components. Such analyses draw on the insights and methods of financial portfolio theory (Markowitz 1952; Sharpe 1964), which focus on the process of investment diversification or 'hedging' as a means to reduce the sensitivity of an overall investment portfolio to the fluctuations of individual stocks.

Though urban water portfolios are quite different to financial portfolios in many ways, the underlying concepts have been applied to demonstrate the potential value of functional diversification to the urban water problem (Wolff 2008; also see Marinoni, Adkins & Hajkowicz 2011). Three options were assessed for augmenting an existing run-of-river system: an advanced treatment process could be used to recycle wastewater or desalinate seawater, the river surface water source could be augmented by providing new pumping equipment, and a demand management program could be implemented to reduce outdoor demand. As the recycling / desalination option is largely 'climate independent', it was deemed to possess negligible correlation with the existing portfolio and would therefore be required to provide roughly the same additional capacity to that expected within a conventional deterministic analysis. The surface water augmentation on the other hand was highly correlated with the existing portfolio as it was similarly affected during critical drought years. This option therefore needed to provide roughly 50% extra average capacity to provide a similar standard of reliability, making its effective unit cost 50% higher when compared in terms of average yields. Conversely the outdoor demand management option was observed to be negatively correlated with the existing portfolio as it will provide a higher yield relative to the existing surface water portfolio during critical drought years (outdoor demand is typically highest during droughts owing to increased crop evapotranspiration, assuming no water restrictions are in place). As such the outdoor demand management program only needed to provide 86% of the capacity predicted in the deterministic analysis, and therefore had an equivalent reliability-adjusted unit cost 14% lower than its deterministic unit cost.

Similar analyses have been undertaken in the energy sector. For instance, it has been demonstrated that adding renewable generation to a fuel-dependent energy supply portfolio can reduce its overall risk-adjusted cost profile despite possessing a higher 'unit cost' (Awerbuch 2006). This occurs primarily because the uncertainties of renewable generation yields are largely uncorrelated with those of fuel-dependent sources such as natural gas and coal. Renewable sources therefore offer an effective 'hedging' benefit which reduces the overall sensitivity of the supply portfolio to fuel supply volatility.

Such analyses confirm that while highly correlated components will lead to systemic reliabilities that are lower than their individually assessed reliabilities, poorly correlated components will typically lead to sensitivities that compensate for one another, leading to systemic reliabilities that are stronger than would be implied by their individually assessed reliabilities. Planners and designers can therefore design more affordable and reliable resource strategies through portfolio diversification than simply adding redundant capacity.

4.3.2 Structural complexity

The mechanism of structural complexity highlights the configuration of system components and their relative vulnerability to variability and fluctuation.

Conventional centralised energy and water systems adopt a 'radial' configuration whereby supplies are connected to transmission links that are sequentially branched off to connect to individual households. This configuration is vulnerable to variability and fluctuation owing to the large sequence of nodes and links that must be reliably maintained to preserve service levels across the network. To address this vulnerability, network planners typically include redundant network connections or 'looping' (Swamee & Sharma 2008).

A diverse sequence of analytical methods has been brought to bear on the problem of optimising the level of redundancy across urban water and energy networks, from so-called topological or connectivity analyses that assess the probability of maintaining connectivity between a given demand node and any suitable supply node, to the much more comprehensive probabilistic network analyses which assess the probability of maintaining sufficient flow subject to individual component failures (Ostfeld 2004; Gertzbakh & Shpungin 2009).

The limitation of network redundancy as a response to variability and fluctuation is that it is inherently in tension with the objective of maintaining efficient network linkages (i.e. as outlined in the mechanism of structural integrity described above). Furthermore, as outlined in the review of structural complexity in the previous chapter, too much network connectivity can counter-intuitively amplify network failures, leading to cascading failure and instability (for further detail see the analysis of structural modularity below). Reconciling these tensions requires a more integrated approach, detailed below.

4.3.3 Designing for resistance

Similar to the analysis of ascendance mechanisms above, the analysis above demonstrates that each of the two mechanisms observed to underlie resistance can be recognised in emerging urban water and energy planning theory and practice.

However, the true value of the framework is in highlighting the synergies that arise from aligning the functional and structural mechanisms to create integrated solutions. As reviewed in the previous chapter, analyses of the relative stability of alternative ecological networks have identified networks comprising a series of components with overlapping spatial and temporal scales. These networks offer sufficient negative feedback for improved local stability while minimising the challenges of 'over-connectedness' such as resource inefficiency and cascading failure.

Applied to the context of urban water and energy systems, such a configuration could offer the prospect of facilitating mutual support across zones and between scales while simultaneously reducing the sequence of components necessary for maintaining connectivity. This 'distributed infrastructure' configuration therefore offers the prospect of delivering an improved level of systemic resistance to variability and fluctuation at a lower cost than the traditional approach of adding network redundancy alone.

While no clear analytical case studies have been undertaken to demonstrate the value of this approach, Yazdani and Jeffrey's conception of 'accessibility' (2011) offers a useful metaphor and proxy indicator for how reliability could be improved in this way. Originally proposed in the field of transport network analysis (see e.g. Black 2003; Geurs, Krizek & Reggiani 2012), accessibility describes the set of journeys or network paths necessary to meet all the requirements of an activity node. By distributing sources across the network (i.e. by improving 'accessibility'), the critical network path is reduced, thereby reducing the tension between reliability and network efficiency. Structural complexity theory significantly extends the concept of accessibility by identifying how certain system assemblies provide cross-scale reinforcement, and therefore how they may be efficiently designed for specific sets of fluctuations.

The limitation of resistance and its constituent mechanisms is its inability to cope with surprise shocks and shifts that cannot be anticipated or planned for. Such situations require consideration of resilience concepts, described below.

4.4 Resilience: performance subject to shocks and shifts

Over a long enough time-scale, some degree of surprise is inevitable in urban water and energy systems owing to our limited ability to anticipate the future. Step shifts may occur in the climate owing to anthropogenic greenhouse emissions and other changes; populations and economies may change in size and form; disruptive technologies may provide new challenges and opportunities; and unforeseen shocks, natural disasters and terrorist attacks can lead to partial or catastrophic failure.

'Resilience' describes the ability of a system to adapt with these shocks and shifts and is therefore a principal concern of urban water and energy planners.

Resilience is distinguished from conventional risk management responses in its qualitatively different stance to shocks and shifts. Whereas conventional risk management approaches adopt a defensive stance to shocks and shifts (i.e. risks are 'managed'), resilience emphasises the capacity of systems to dynamically exploit conditions as they arise.

The conceptual framework identified two conceptual mechanisms underlying resilience to surprise shocks and shifts: functional flexibility and structural modularity.

4.4.1 Functional flexibility

The mechanism of functional flexibility implies the development of functional contingencies suitable for addressing a suite of possible shocks and shifts in conditions, and is closely aligned with notions of 'plasticity' in biology and ecology and 'managerial flexibility' in financial and economic theory.

In the context of water and energy planning the mechanism of functional flexibility draws attention to the value of developing and maintaining contingent options in readiness for a range of future conditions. For instance, urban water planners in drought-affected regions commonly develop a suite of contingencies for a suite of possible drought scenarios. Contingency response options are also applied in the energy sector to prepare for widespread outages and other failures. By effectively deferring the planned actions to the latest possible safe point in time, urban water and energy planners can preserve their managerial flexibility and simultaneously minimise the likelihood of a regretful decision.

Analytically, the mechanism highlights the advantages of comparing the flexibility of alternative infrastructure strategies. An example of such an analysis was provided by an urban water case study (Borison & Hamm 2008). Three options were assessed: a dam, a desalination plant, and a wastewater recycling plant. These were further broken down into 'stages' or decision points such as initial feasibility studies and augmentations. Several significant uncertainties that emerged from an initial sensitivity analysis were analysed in detail. These included dam feasibility, recycling feasibility, desalination plant cost and catchment inflow. Uncertainties were specified 'conditionally' where required; that is, time-dependent uncertainties associated with an element of learning such as catchment inflow were modelled to account for additional information arising in the future using Bayesian probability conditioning methods. These uncertainties and options were then incorporated within a tree-based decision optimisation procedure. It was found that the water resource portfolio that was optimised to exploit flexibility provided a significantly reduced risk profile, with a 10% reduction in the overall risk exposure relative to the strategy that applied portfolio diversification alone (also see Hobbs, Chao & Venkatesh 1997; Huang, Vairavamoorthy & Tsegaye 2010).

A similar hypothetical analysis has also been undertaken in an energy planning context (Borison & Hamm 2005). The case study described a negotiation for a 20-year supply contract between an energy retailer ABC Power and a generator XYZ Generation. Three alternative analyses were undertaken to highlight the benefits of analysing and designing for flexibility. Initially a baseline analysis was conducted using nominal values. It indicated a negative net present value, suggesting that the contract compared unfavourably to the spot market if uncertainty was disregarded. Secondly, a probabilistic uncertainty analysis was undertaken to incorporate three principal uncertainties (nuclear availability, electricity prices, and transmission regulation), yielding a wide distribution of net present values from a low of –$100 million to a high of $100 million, with an expected value of –$25 million, suggesting that the contract was still unfavourable if flexibility was disregarded. Finally, an option analysis was undertaken to explore the value of retaining the option to terminate contracts early, if conditions were unfavourable. This more flexible contractual position indicated an expected net present value of $15 million.

Though these sorts of analyses represent additional complexity to energy and water planners, they demonstrate the clear opportunities for functional flexibility to reduce both risk and cost in situations characterised by high levels of learning and surprise.

4.4.2 Structural modularity

The mechanism of structural modularity implies the assembly of systems comprising semi-autonomous, separable and combinable functional components.

In the context of water and energy planning the mechanism of structural modularity highlights the value of an incremental growth strategy. For instance, an urban wastewater system comprising a series of relatively small incremental collection zones with smaller treatment modules can more readily match requirements as they arise than a more traditional wastewater treatment plant. This superior ability to respond to changed requirements reduces the risk of insufficient or surplus capacity if future treatment capacity requirements are above or below that predicted.

The same can be said of energy systems. That is, more modular energy systems comprising many smaller electricity generators or network augmentations can more readily match electricity loads as they arise, thereby reducing reliance on the accuracy of long-term demand projections.

Modular structures also offer a degree of autonomy and separability among components, enabling them to 'fail gracefully', thereby reducing their exposure to cascading failures and other system-wide disruptions. For instance energy networks comprising a series of semi-autonomous modules or zones are more readily capable of isolating or 'islanding' local failures and thereby limiting their translation across the network to cause rolling blackouts or 'cascading failures' (Koch et al. 2010).

This phenomenon has also been observed as a potential benefit of more decentralised wastewater systems (Fane, Ashbolt & White 2002). Though such systems may exhibit a higher probability of failure, such failures are usually less impactful as they are localised to a small number of households. On the other hand, the failure for a conventional centralised wastewater system, though less likely, may be much more impactful from a human and ecological health risk perspective.

No specific analytical case studies for assessing structural modularity have been found, however there are several prospective methods in the fields of graph theory. So-called 'network clustering algorithms' have been developed to identify ideal locations for divisions among the 'clusters' comprising a given system (Newman & Girvan 2004). Central to these analyses is a measure for the 'betweenness' or relative centrality at given locations across the network, which ultimately provides a quantitative indicator for natural divisions across a network (Freeman 1977). Although no specific application of these methods to urban water or energy planning has been found, these methods may offer the prospect of analysing and designing for structural modularity.

4.4.3 Designing for resilience

Consistent with the mechanisms of ascendance and resistance, the conceptual framework suggests synergies are likely to arise if functional flexibility and structural modularity are aligned into an integrated approach.

In the context of urban water and energy planning the mechanisms elicit the possibility for using contingent 'policies' or decision logics instead of conventionally scheduled infrastructure investments. For instance, instead of specifying the rollout of infrastructure in a sequence of modular stages, the stages could be specified more effectively as a series of triggers or decision logics, thereby preserving a degree of flexibility to adjust to conditions as they arise.

Although examples of contingency-based approaches to long-term planning studies are still quite rare, a recent case study in the Australian water sector provides an illustration of the possibilities (Mukheibir et al. 2012). The context of the analysis was a coastal metropolitan water system subject to a high level of interannual variability in rainfall, and a potentially shifting climate. The existing water resource options were configured into investment strategies governed by alternative decision logics or policies. For instance, one strategy relied on a 'reactive' approach in which large supply augmentations were implemented in response to supply-demand shortfalls, while another adopted a 'proactive' approach that emphasised incremental investments triggered as opportunities arise (e.g. new green field developments often provide cost-effective decentralised wastewater treatment and reuse opportunities). The different strategies were then exposed to a suite of prepared scenarios characterising the future climate, demand and costs and their relative performance was analysed. The analysis found that the 'proactive' strategy was slightly more costly under the low severity scenario but when compared across the entire scenario ensemble provided much better performance than the comparatively lumpy response of the reactive strategy.

This shift in planning practice will likely require stronger linkages between short-term contingency planning and long-term strategic planning, however the potential benefits in terms of reduced cost and risk exposure are clear.

4.5 Discussion

The conceptual framework identified in the previous chapter appears to provide a relevant and potentially insightful 'thinking tool' for analysing and designing urban water and energy systems.

By analysing each of the identified attributes in the context of urban water and energy systems it has been shown that the attributes provide a more systemic perspective of performance. Furthermore the important distinction between resistance and resilience has been shown to be just as instructive in urban water and energy systems as it is in economic and ecological systems.

The conceptual framework described in this thesis also provides a set of potentially instructive design patterns for embedding the insights of ecology and economics in urban water and energy systems. While most of the identified mechanisms have an equivalent paradigm in urban water and energy planning, the framework provides a conceptual model to motivate, situate and connect those approaches. For instance, while the notion of flexibility is receiving increased attention from water and energy utilities, this attention is not necessarily connected to its structural complement, structural modularity. Similarly, while the concept of a 'diversified portfolio' is becoming increasingly widespread, its relationship with the less understood concept of structural complexity is less well elaborated. The conceptual framework suggests that the functional and structural mechanisms mutually reinforce one another and, inversely, that exclusively focussing on one mechanism may preclude the realisation of their full benefits.

Furthermore the conceptual framework highlights the potential tensions between the mechanisms. For instance, while 'diversity' and 'flexibility' are commonly used in the same sentence by energy and water planners, the framework highlights their different roles in contributing to systemic performance. While a diversified portfolio is well suited for resisting fluctuations and variability, it is likely to lead to false confidence and overinvestment when applied to resisting surprise shocks and shifts. Similarly, the conceptual framework highlights that a highly connected network topology, while providing strong reliability subject to typical fluctuations, will likely prove to be quite vulnerable to cascading failure without consideration for structural modularity.

However, a key test of a conceptual model for systemic performance lies in its practical translation into a diagnostic and prescriptive tool. The next chapter therefore seeks to identify a set of analytical methods to assess the various attributes and in so doing it seeks to provide a possible pathway forward for urban water and energy planning and design.

5 Analyses: a synthesis of analytical methods for assessing urban water and energy systems

5.1 Introduction

In integrating the insights from the two systems sciences of ecology and economics, the conceptual framework provides a coherent perspective for analysing ecological and economic systems, including the metabolisms of energy, water and other materials that sustain our cities and societies.

However, effectively operationalising these new performance concepts will only be possible if we have a set of corresponding analytical methods with which to assess them.

This chapter therefore builds on the conceptual framework by investigating a broad suite of analytical methods for assessing each of the attributes proposed in the previous conceptual framework.

The analysis presented here differs from earlier works of a similar nature (van den Bergh & Nijkamp 1991; Boulanger & Bréchet 2005) in three important ways: firstly, in the diversity of fields from which the methods are drawn; secondly, in its agnostic treatment of the relative strengths and limitations of analytical methods, including whether objectives should be assigned monetary values and whether uncertainties should be quantified using probabilities; and thirdly in the breadth of attributes it seeks to address, including the important but analytically challenging aspects of resilience.

The chapter begins by identifying a relevant suite of methods for assessing each of the attributes, including an analysis of each method's strengths, limitations and effective role. An overview is then provided, together with a description of how the methods may be practically applied to structure assessments and evaluations. A discussion follows on the strengths and limitations of the review, together with some concluding remarks.

5.2 Assessing ascendance

As described in Chapter 3, this thesis defines ascendance as the necessity for ecological and economic systems to exploit, efficiently process and/or recirculate sufficient resources to maintain and develop their functions and structures.

A broad suite of candidate methods for assessing the ascendance of systems is identified and analysed below. Firstly, a set of assessment methods is identified for assessing the 'ecological ascendance' of systems, which focuses on analysing physical stocks and flows and ecological impacts. Secondly, a set of methods is identified for assessing the 'economic ascendance' of systems, which 'wrap' the ecological ascendance assessment with an assessment of human values in the form of financial stocks and flows and non-market impacts as shown in Figure 11.

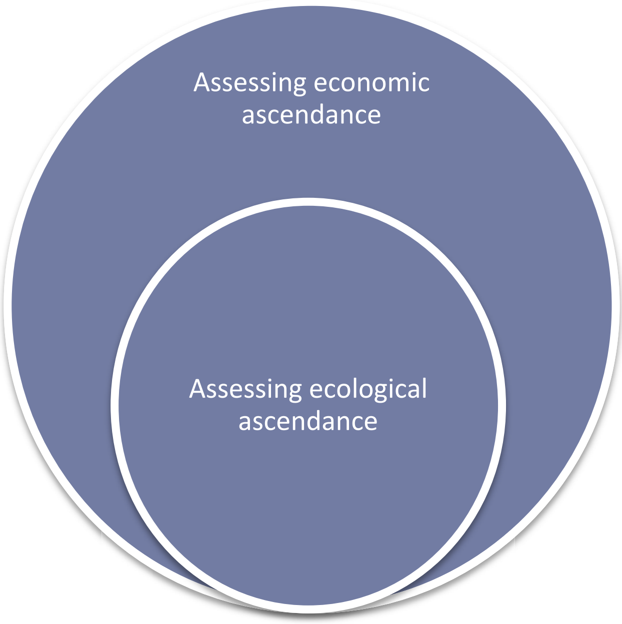

Figure 11 – Systems diagram of the relationship between economic and ecological ascendance

It is important to stress that the diagram does not imply that economic ascendance usurps or dominates ecological ascendance. Rather, economic ascendance includes and extends ecological ascendance by adding a higher dimension to the assessment. In systems language ecological ascendance may be described as being more 'fundamental' in circumscribing the physically possible configurations of the system, while economic ascendance may be described as being more 'significant' in directing the specific form of the system among the myriad physically possible forms.

5.2.1 Assessing ecological ascendance

This section investigates a series of candidate methods that focus on analysing physical stocks and flows and ecological impacts.

A fundamental stage underlying all the surveyed methods involves quantifying the material and energy[6] flows through and within the system using ***material flow analysis***[7] (MFA)

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[6] Opinions vary as to whether an analysis of energy flows can be technically described as material flow analysis and the term 'energy accounting' is often preferred. For the purposes of this thesis the terms will be used synonymously.

(Baccini & Brunner 1991; Brunner & Rechberger 2003). The method firstly involves identifying the relevant activities and processes associated with the defined material/s occurring within the system boundary. Material intensities are then assigned to each of those activities and processes to derive their associated material flows. Those flows are then aggregated to analyse the total flows of the material and/or energy within and across the system boundary.

However, the method has a number of limitations that can restrict its application on a standalone basis. Firstly, the method typically avoids consideration of the underlying function or objective of the system. A foundational insight of ascendance theory is that each system is a part of a hierarchy of mutually supporting systems (Ulanowicz 1997). As such, it is important that any changes to the system being assessed do not systematically undermine its function with respect to these supporting systems. When MFA is used by itself, there is no guarantee that this undermining will not take place.

Secondly, the method does not by itself offer a means for translating material and energetic flows into ecological impacts. Drawing once again on the hierarchical notions of ascendance theory, it is important that the system under analysis does not undermine the various ecological, economic and social systems in which it is embedded. Although MFA provides an effective accounting framework, its results require either expert interpretation to interpret priorities and safe thresholds, or complementary analytical methods to translate those expert interpretations into quantitative criteria. Three methods are reviewed below as candidate complementary methods: material input per unit service analysis, ecological footprint analysis and life cycle analysis.

Material input per service unit analysis (MIPS)[8] assesses the flows of a defined material or materials associated with a defined service or product (Schmidt-Bleek 1993b, 1993a). The method involves initially specifying an appropriate unit of service for which the impact will be assessed. For specific services, this may be self-evident, however for products an equivalent unit of service must be established (e.g. for a car one might apply the passenger-kilometre). The direct volume of material required to produce that unit of service is then calculated. Finally material intensity factors are assigned to translate direct material inputs into indirect material masses across several categories (e.g. biotic and abiotic material, soil, water and air).

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[7] Related methods include substance flow analysis, material flux analysis, material flow accounting, and end use analysis.
[8] Also referred to as the 'Rucksack Method'.

The strength of MIPS for assessing ecological ascendance is in providing an easily understood indicator for the material efficiency of a service or product. That is, MIPS is focussed, not just on quantifying the throughput of the system as in MFA, but also on the efficiency of the throughput in fulfilling its specified function.

However, the method's exclusive focus on input flows provides a partial perspective of the ascendance of the system on two counts. Firstly, by avoiding any consideration of the outputs of the system, the method ignores the relative impacts of different waste flows to ecosystems. Secondly, by failing to distinguish between recirculated inputs and raw inputs, the method systematically ignores opportunities to recirculate resources – a key mechanism that has been observed to underlie sustained increases in the function of ecological and economic systems subject to resource scarcity. MIPS therefore represents a partial perspective of ecological ascendance.

Ecological footprint analysis (EFA) assesses the equivalent biologically productive land area necessary to regenerate and render benign the material and energy consumed and released by a defined system (Rees 1992; Wackernagel & Rees 1996).

This method involves initially conducting an inventory to assess the types and quantities of the energy and materials consumed and released by the defined system. These various flows are then assigned equivalent productive land areas (e.g. for energy one can apply an equivalent biofuel crop). These equivalent land areas are totalled to calculate the equivalent productive land area to maintain the system.

The strength of ecological footprint analysis for assessing ecological ascendance is in providing an easily understood and readily comparable indicator for the 'scale' of the system including the impact of both the input and output streams. In so doing, the method provides a means for assessing the whether a system's resource inputs and outputs overshoot the capacity of its supporting ecosystems – a key consideration of ascendance assessment.

However, by assuming a complete reliance on biological substitution the method has a tendency to systematically downplay the role of technological innovation. Further, by conflating the impact categories into this consolidated metric many important qualitative and contextual distinctions between different flow streams and impacts may be obscured (McManus & Haughton 2006). For example, the relative availability of key resources such as water and nutrients varies considerably from region to region. The ecological impact of a water flow compared to a nutrient flow will therefore also differ considerably from region to region. The method is therefore not ideal for comparing the system throughputs to local resource and ecosystem thresholds.

Life cycle analysis[9] (LCA) assesses the environmental impact of a product or service including all phases of production, use and disposal (SAIC 2006). The method involves firstly defining the good or service together with the boundaries of the study. The material and energy inputs and releases over the life cycle of the good or service are then identified and quantified. The relative impact of each of these flows is then quantified using a consolidated impact score or set of scores across various impact categories (e.g. greenhouse effect, acidification, eco-toxicity, human toxicity, ozone depletion, eutrophication, smog etc.).

The strength of life cycle analysis for assessing ecological ascendance is in providing a readily comparable quantitative criterion (or criteria) characterising the total ecological impact of a system, including the materials embodied within that system's structure or form. In so doing the method can provide the analytical foundation for quantitatively optimising ecological performance characteristics and dramatically simplifying the subsequent interpretation of the results.

However, the process of assessing the impact of various material and energy flows can lead to a range of issues. Similar to ecological footprint analysis, the spatial and temporal variation of impacts is often disregarded (Reap et al. 2008), removing the opportunity to incorporate local ecological thresholds (Muradian 2001). The method is also poorly suited to assessing systemic (rather than marginal) changes, since the assessment of environmental impacts assumes no structural change within the economy.

Another key issue with the application of life cycle analysis is the challenge of combining the various impact considerations into a useable criterion or set of criteria (Reap et al. 2008). A variety of approaches have been suggested for addressing this problem, including reducing all impact categories into energy equivalents, multi-criteria analysis methods that dimensionally reduce impact categories into a consolidated impact score, and non-market valuation methods that integrate ecological impacts within monetary criteria.

The core strength of the energy equivalent LCA approach is that all ecological flows may be expressed in a form which enables a simple comparison according to single criterion. However, energy equivalence measures provide a partial indicator of ecological impact and omit important distinctions around different material and energy flows and their impacts on

[9] Also known as life cycle assessment

local ecosystems (Ayres 1995). Energy equivalence measures are therefore better framed as complementary indicators for informing an assessment of ecological ascendance.

As distinct from the energy equivalent approach, the multi-criteria LCA approach provides the space for qualitatively different material flows to be assessed in their context through expert judgement and/or deliberation. However, as described above, such assessments may be challenging in situations with a large number of ecological impacts, particularly when other facets of the assessment are included.

As distinct from the two other approaches, non-market valuation LCAs provide an output that may be readily incorporated into economic assessment criteria. The approach is therefore quite suitable for an integrated assessment of ecological and economic ascendance. However, the process of translating ecological flows into monetary values can be challenging and may be associated with critical issues (Pelletier & Tyedmers 2011).

The most obvious of these from the perspective of ecological ascendance assessment is that the valuation of ecological impacts is typically established by aggregating the individual choices of a large sample of individuals (so-called ‘choice modelling’). Such studies typically under-represent ecological objectives against economic objectives – partly because they capture individual rather than collective values and partly because the individuals in the sample typically don’t have the time or information to understand the complexity of ecological impacts (Spash 2007). However, given sufficient time and resources these limitations may be significantly addressed by employing valuation methods that incorporate collective deliberation (Álvarez-Farizo & Hanley 2006).

The decision as to which specific methods will be applied for assessing ecological ascendance will largely depend on the objectives of interest. If the objective is associated with distinct ecological thresholds, if the assignment of quantitative impact criteria is inappropriate or impractical, or if a market already exists for the defined resource then MFA is likely to be sufficient. If no existing market is available to sufficiently capture the impact and the resource flow is amenable to optimisation in impact criteria, then LCA is likely to be the most suitable response, using MCA scoring or monetisation. MIPS and EFA are better placed as complementary indicators for providing an easily interpretable and comparable indicator of ecological efficiency and scale, respectively.

To provide a specific water or energy planning example, it may be the case that an existing price has been established for a given pollutant (e.g. greenhouse gas or nutrient emissions) through an emissions tax or trading scheme. If the price is judged to adequately reflect the environmental impact of that emission, then material flow analysis alone may be sufficient. If no such price has been established and a proxy price is difficult to quantify, then a comprehensive life cycle analysis may be necessary to account for the direct and indirect impacts of alternative policies.

While the above methods are effective for analysing material and energy flows and impacts, a form of economic analysis is necessary for analysing financial flows and non-market costs and benefits, as discussed below.

5.2.2 Assessing economic ascendance

Economic ascendance is primarily a concern for systems involving significant financial scarcity, competition and/or non-market economic impacts. This section therefore analyses a set of candidate methods for assessing financial flows and non-market benefits and costs.

A fundamental method for assessing economic ascendance involves identifying the financial flows through and within the system using ***cash flow analysis*** (Speed 1997). The method involves firstly identifying the relevant activities and processes associated with the defined entity or entities occurring within the system boundary. Unit rates or financial intensities are then assigned to each of those activities and processes to derive their associated financial flows. Each of those flows is then aggregated to analyse the net balance of financial flows to each entity of concern and therefore their ongoing financial viability.

The strength of cash flow analysis is its ability to analyse the financial flows to and from key stakeholders affected by a policy or strategy. The method is therefore well suited to assessing the financial viability of systems from the perspective of a range of affected stakeholders. It can also analyse the distribution of costs and benefits of a given strategy and whether a shift in transfer payments is justified. That is, if the strategy is desirable from a whole of society perspective but not for a given affected stakeholder, then cash flow analysis can provide the evidence to renegotiate payments and ensure incentives are aligned.

However, by constraining the assessment to consider financial flows alone, cash flow analysis may exclude many potentially important non-market benefits and costs from the assessment, necessitating its extension within either a cost-effectiveness analysis or cost-benefit analysis.

Cost-effectiveness analysis[10] (CEA) assesses the economic efficiency of alternative strategies for meeting a defined objective or set of objectives (Foster & Hoeber 1955; USEPA 2010). The method involves initially establishing a set of objectives in the form of a set of targets and constraints using a suitable external decision-making process. Alternative strategies for meeting those objectives are then identified. The direct benefits and costs arising from those strategies are then assigned monetary values. These costs and benefits are then expressed, typically in present value terms using discounted cash flow analysis and they are compared on the basis of their cost-effectiveness ratio (for individual portfolio components) or net cost-effectiveness (for a portfolio of components that satisfy the objectives).

The strength of cost-effectiveness analysis for the purpose of assessing economic ascendance is its ability to identify the relative cost of reaching a set of consistent targets and constraints. It is therefore well suited to assessing ecological-economic systems driven by externally established societal or ecological thresholds that are often difficult or inappropriate to include in the quantitative criteria. Furthermore, the method obviates the need to undertake the analytically challenging and often contested exercise of monetising the core benefit of a policy (e.g. water or energy supplied) as this objective is directly incorporated in the objectives as a constraint.

However, by incorporating the objectives as fixed targets and constraints, the method is unable to quantitatively assess the optimal level at which the objectives should be established (e.g. by providing a higher or lower level of service than specified), or indeed whether the objectives should be pursued at all.

Cost-benefit analysis[11] (CBA) extends cost-effectiveness analysis by assessing the total benefits against the total costs of a strategy or set of alternative strategies (McKean 1958; Hanley & Spash 1993b; Pearce, Atkinson & Mourato 2006). The method involves initially identifying a strategy or set of alternative strategies for meeting an objective or set of objectives. These objectives, together with all other benefits and costs associated with the strategy or strategies, are then assigned monetary values, assigning proxy market values where necessary using non-market valuation methods. The strategy or set of alternative strategies is then assessed on the basis of its benefit-cost ratio (i.e. benefits / costs).

[10] Also known as cost-efficiency analysis
[11] Also known as benefit-cost analysis (BCA) or cost-benefit assessment

The outputs of a cost-benefit analysis have a set of additional capabilities that set it apart from cost-effectiveness analysis. Where cost-effectiveness analysis assesses a set of alternative strategies with equivalent objectives, cost-benefit analysis may be applied to assess a set of strategies with differing objectives (e.g. comparing an improvement in water quality standards to an improvement in electricity reliability). The method can also assess alternatives which have differing performance levels in meeting the objectives (e.g. strategies that provide different levels of electricity reliability). Ultimately therefore, cost-benefit analysis can assess what level of performance is justified by the costs. Finally, the cost-benefit ratio may be applied to assess specific policies in isolation – that is, whether the benefits of an individual policy justify the costs.

However, the additional analytical insight of cost-benefit analysis comes at a considerable cost, both in terms of additional analytical effort and in the nature of the assumptions it employs.

The foundational assumption is that all significant benefits and costs of the strategy are adequately reflected in their monetary values. This is a considerable challenge for the purposes of assessing the ascendance of ecological-economic systems owing to a number of challenges in quantifying ecological impacts. Firstly, the state of knowledge of the underlying dynamics of ecosystems is often poor. Secondly, where the underlying dynamics of ecosystem impacts are well studied they are typically characterised by high levels of non-linearity and threshold behaviour (Muradian 2001). Both of these challenges make the assignment of quantitative objective functions to ecological impacts a highly contested and challenging exercise.

Secondly, the method typically assumes that all benefits and costs are substitutable for the purposes of maximising welfare (Wegner & Pascual 2011). Without due care the method can therefore lead to unacceptable trade-offs that may ultimately degrade ascendance. For instance, by conflating all impacts into a single quantitative criterion the decision-maker could offset the irreversible degradation of an ecosystem with improved recreational amenity.

Thirdly and critically, the method typically relies on the application of discount rates to express future costs and benefits in terms of their 'present value' (Hanley & Spash 1993a). This is a problematic area for the purposes of assessing ascendance as ecosystem services and natural capital are often non-substitutable and their degradation is often irreversible, rendering the standard discounting approaches unacceptable from an intergenerational equity standpoint (Lind 1995).

However, cost-benefit analysis offers a prospective pathway to quantitatively assessing the ascendance of ecological-economic systems given appropriate modifications. For instance non-market valuation functions may be designed to attempt to reflect the true non-linearity and irreversibility of ecosystem impacts (McConnell 1995). Furthermore, differential discount rates may be applied to avoid discounting the quality of ecosystem services and natural capital available to future generations (USEPA 2010).

In summary, cost-effectiveness analysis is effective where the level of the driving objectives is best defined as a fixed constraint established outside the quantitative analysis process, or where the monetary valuation of objectives is inappropriate or objectionable. Cost-benefit analysis, on the other hand, is effective where the objectives are best analysed within the quantitative assessment and where the monetary valuation of all significant objectives and impacts is judged to be appropriate.

In practice the two methods may be usefully applied in combination to offset their respective limitations. That is, a carefully executed cost-benefit analysis may be applied as a tool to inform a strategic assessment of appropriate priorities and objectives at less frequent decision junctures, whereas cost-effectiveness analysis may be applied more frequently for identifying least-cost strategies for meeting established objectives.

5.2.3 Integrating economic and ecological ascendance

Though the delineation between ‘ecological ascendance’ and ‘economic ascendance’ is conceptually convenient, ecological and economic systems are in reality rarely distinct and are typically associated with significant connections and feedbacks (Costanza et al. 1993). As such any integrated assessment process will necessarily cross both domains.

One useful approach for bridging the physical and economic domains is to identify discrete functions or activities for which both physical and economic resource intensities can be meaningfully assigned with respect to specific processes, technologies and practices.

This approach is employed extensively in the so-called ‘activity modelling’ or ‘end-use modelling’ analytical method extensively employed for modelling water, energy, and other urban resource systems (Billings & Jones 1996; Farahbakhsh, Ugursal & Fung 1998; Turner 2003). The consumption of the resource is disaggregated into discrete resource-consuming activities or ‘end uses’ including specific agricultural, industrial, commercial, and residential processes such as ‘residential showering’, ‘commercial cooling’ and ‘steel production’. Physical and financial resource intensities are then assigned to each of these end-uses to determine the physical and financial flows associated with the system.

The physical and economic assessments may then be integrated by one of three means.

In situations where an economic market already exists for the input or output then ecological impacts may be incorporated into the assessment criteria as monetary values. A clear example of this is where a price has been established for the emission of greenhouse gasses or the disposal of nutrients to waterways. The benefit of monetisation is that the outputs may be readily integrated within the quantitative analyses of economic ascendance. However, this form of monetisation relies on the assumption that all ecological and societal impacts have been effectively internalised within the market price. This assumption should always be made carefully owing to the widespread presence of externalities (Pearce 1976; Hanley, Spash & Cullen 1993).

Where an appropriate market for the ecological impacts is unavailable it may be possible to incorporate them indirectly as a set of constraints limiting the suite of alternative strategies. This approach is well suited to assessments with limited analytical resources, or assessments where impacts are marked by distinct ecological thresholds (Muradian 2001). However, owing to their fixed and distinct nature, constraint objectives drive performance toward strategies that meet but don’t necessarily exceed the specified performance constraint, rendering the approach unsuitable for objectives where trade-offs or optimisation are of key interest.

Alternatively, the quantitative flows of materials and energy to and from the system may be preserved as considerations within subsequent deliberation outside the quantitative analysis. This approach offers the benefit of making the ecological impacts of the system explicit, thereby preserving their contextual nuances for subsequent expert judgement and/or deliberation. However, the approach can place a significant responsibility on the deliberation process, particularly when the number of ecological impacts is large.

An assessment of ascendance will typically comprise a series of objectives and impacts, each with distinct characteristics. As such an integrated assessment will typically comprise a mixture of each of these approaches.

Used in isolation, the methods assessed above may be described as *deterministic* as they assume a single possible scenario[12] comprising a fixed sequence of future events. The following section outlines several methods for extending the application of above methods to situations in which this assumption is no longer appropriate.

5.3 Assessing resistance

As described in the previous chapter, systems optimised for a single set of conditions may be inappropriately vulnerable and unstable in environments characterised by variability and fluctuation. Such situations warrant the addition of a means for assessing the relative 'resistance' of systems. Four candidate methods are analysed here for assessing the resistance of systems to variability and fluctuation: sensitivity analysis, scenario analysis, uncertainty analysis and portfolio analysis.

The analytical methods aren't assessment methods in their own right but rather the means for extending the assessment of ascendance for variable conditions. They therefore represent alternative means for 'wrapping' an assessment of resistance around the underlying ascendance assessment as shown in Figure 12 below.

[12] The term *scenario* is applied here to mean a sequence or development of *events*, as distinct from *strategy*, which is used to connote a sequence or development of *actions*

Figure 12 – Systems diagram of the relationship between resistance assessment and ascendance assessment

Sensitivity analysis assesses the performance of systems subject to variance in factors affecting the system objectives (Eschenbach & McKeague 1989; Clemson et al. 1995; Pannell 1997).

The method involves firstly estimating consistently the probable low and high range levels for each factor and iteratively testing them within the assessment process described above. The relative influence of each factor on the performance of alternative strategies may then be assessed quantitatively and/or graphically.

The relative simplicity of sensitivity analysis makes it an ideal method for assessing the variance of the system's performance subject to a large suite of uncertainties. It can therefore provide an indicator for the resistance of a system, while highlighting those disturbances warranting further analysis.

However, in the absence of appropriate extensions, conventionally applied sensitivity analyses ignore the impact of uncertainties in combination (Saltelli 1999). This means that sensitivity analysis may significantly overestimate the overall level of resistance because it does not account for possible covariance among the uncertainties affecting the system.

Sensitivity analysis therefore provides a partial assessment of the resistance of a system to variability and fluctuations, often necessitating either scenario analysis and/or uncertainty analysis.

Scenario analysis assesses the performance of strategies subject to pertinent sequences of future events (van der Heijden 1996; Schwartz 1998; Alcamo 2001).

The method involves initially identifying significant factors likely to influence the objectives of the study, often by using an initial sensitivity analysis. The core drivers underlying those factors are then identified and paths for each driver are developed. These paths or storylines can then be elaborated into scenarios using logical quantitative models.[13] The performance of alternative strategies subject to these scenarios may then be compared.

Owing to the relatively moderate level of quantitative modelling involved, scenario analysis can free up analytical resources to instead focus on creatively exploring the range of possible futures and in doing so reveal insights that lie beyond more formal analytical processes.

However, the method's performance deteriorates when attempting to analyse a large number of uncertainties, owing to the correspondingly large sets of scenarios to be analysed. This can potentially lead to the exclusion of significant uncertainties or to inappropriate attention being given to relatively improbable futures (Kann & Weyant 2000; Vose 2008), often necessitating a form of uncertainty analysis.

Uncertainty analysis[14,15] assesses the performance of strategies subject to a range of alternative futures with specified probabilities (Cooke 1991; Cullen & Frey 1999; Vose 2008).

Similar to scenario analysis the method firstly involves identifying the suite of factors that significantly affect the performance of the system, typically using an initial sensitivity analysis. Probabilities are then assigned to each significant uncertainty, broadly by one of

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[13] The scenario analysis described here is an exploratory, quantitative form. Scenario analyses may also be anticipatory (e.g. hindcasting from desirable future states) and qualitative (e.g. developing storylines and not numerical models) (Pickett et al. 1989).

[14] Also known as probabilistic analysis and quantitative risk analysis. The term 'risk analysis' has been avoided here to prevent possible confusion with 'risk assessment', a term which implies the assessment of the likelihood and impact of the threats to a system or process.

[15] 'Uncertainty' is applied here in the general sense to mean an unknown or indefinite state and therefore includes both current and future states, and both quantifiable and unquantifiable uncertainties. Note this thesis does not apply the terminology commonly applied in economics and finance where 'uncertainty' and 'risk' describe unquantifiable and quantifiable uncertainties, respectively (see Knight 1921) owing to its conflict with the mathematical definition of uncertainty and the engineering definition of risk (i.e. the likelihood and impact of a hazard).

two means: discrete probability weightings which may be assigned to event trees[16] (e.g. high, medium, low); or continuous probability distribution functions which may be assigned to parameters. The overall probability distribution function of the chosen performance metric may then be calculated by analytical convolution, numerical approximation or stochastic simulation[17] and the results for each strategy compared.

As distinct from scenario analysis, uncertainty analysis allows the quantitative assessment of a suite of alternative futures in combination. It is therefore capable of quantitatively analysing a much larger number of significant uncertainties and their interactions.

However, this additional analytical power comes at significant cost in that it requires the probability of each significant uncertain factor to be elicited and appropriately modelled, potentially leading to shortcuts. For instance, the process of identifying an appropriate functional description of uncertainties can be circumvented by uniformly applying normal probability distributions without appropriate analysis of the underlying functional form. Furthermore, the covariance of probability functions may be too challenging to elicit and model and so they may be systematically ignored. Both practices may seem insignificant when an individual uncertainty is analysed in isolation, but they can have a significant bearing on the overall level of systemic risk (Apostolakis & Kaplan 1981).

Without due care the method can also lead to a systematic bias toward analysing relatively probable futures rather than relatively improbable but potentially important futures. This occurs for a variety of reasons but fundamentally it has been found that people struggle to estimate the probability and cost of improbable but severe events (O'Hagan et al. 2006). As such these catastrophic events may be more effectively included within the scenario analysis as a series of 'black swan' scenarios (Taleb 2010).

Portfolio analysis[18] is an analytical method drawn from the financial sector that seeks to maximise the return of a portfolio of investments for a given amount of portfolio uncertainty (Ringer et al. 2007; Bazilian & Roques 2009).

As distinct from uncertainty analysis, portfolio analysis quantifies the uncertainty associated with investments from the 'top-down' by estimating the historical variability or 'volatility' of

[16] The event tree method is sometimes referred as a *contingency tree* (Alcamo 2001), though this term has been avoided to prevent possible confusion with methods that assess the dynamic responses of strategies such as in *contingency analysis* (see below).
[17] Also referred to as Monte Carlo simulation.
[18] Also known as Modern Portfolio Theory

its yield and its covariance with a series of alternative investments. The process then involves the progressive selection of those investments that in combination lead to the highest return for a specified acceptable level of portfolio risk.

However, the method employs a range of quite strict assumptions that can limit its applicability to many 'real' investment problems. For instance the method assumes all investments are able to be divided into infinitely small investment holdings (i.e. they are 'continuously divisible')[19] and can be acted on or changed at any point in time (i.e. they are 'liquid'). Both of these assumptions are problematic when applied to lumpy and often irreversible project investments (Allan et al. 2011). Although these assumptions may be less significant for large-scale policy assessments, they render the method unsuitable for detailed assessments comprising a limited set of options.

Furthermore, the method's reliance on historical market data for characterising the volatility of options is often impractical or undesirable (Jansen, Beurskens & Van Tilburg 2006). Either no suitable real or proxy market is available or, where that data is available, the underlying assumption of stationarity (i.e. that past behaviour represents a suitable model for future behaviour) may be inappropriate.

However, despite these limitations portfolio analysis does offer a valuable framework for optimising the diversification of physical and financial yields for improved resistance to fluctuation. Specifically, the conceptual framework identified in the previous chapter emphasises that the resistance of a system is much more nuanced than a trade-off between yield and risk. Rather, a sophisticated diversification can, to a certain extent, simultaneously improve yield and reduce risk.

In summary:

- Sensitivity analysis is effective for providing an initial indicator of the robustness of systems to a large suite of largely independent uncertainties and for identifying key uncertainties for subsequent analysis.
- Scenario analysis is effective for analysing the combined impact of a limited number of significant uncertainties or where the assignment of quantitative probabilities is inappropriate or impractical.

[19] That is, able to be divided into infinitely small share holdings

- Uncertainty analysis is most effective for analysing a large number of significant uncertainties and where uncertainty ranges may be quantified within an acceptable level of ignorance.
- Portfolio analysis is effective for analysing the effective diversity of systems, particularly for large policy scales.

In practice the methods may be usefully applied in combination to combine their respective strengths. That is, sensitivity analysis may be effectively applied to provide a preliminary assessment of resistance and to reveal which factors warrant further analysis, while uncertainty analysis and scenario analysis may be applied to assess the relative resistance of alternative strategies subject to futures with quantifiable probabilities (e.g. many biophysical behaviours such as temperature, rainfall and runoff generation) and unquantifiable probabilities (e.g. sociotechnical behaviours such as economic activity, technology change), respectively.

The analytical methods assessed above may be described as *passive* as they assume each alternative strategy comprises a series of predetermined actions that cannot respond to new information available in the future. The following section assesses several methods for extending the above analyses for situations when this assumption is no longer appropriate.

5.4 Assessing resilience

As described in the previous chapter, strategies based on fixed sequences of actions may provide little flexibility to respond to surprise shocks and shifts in conditions and they may be inappropriately vulnerable to catastrophic failure. A means of assessing the relative 'resilience' of strategies is therefore warranted. Three candidate methods for assessing the resilience of systems subject to surprise shocks and shifts are identified and analysed: *contingency analysis, decision analysis and real options analysis*.

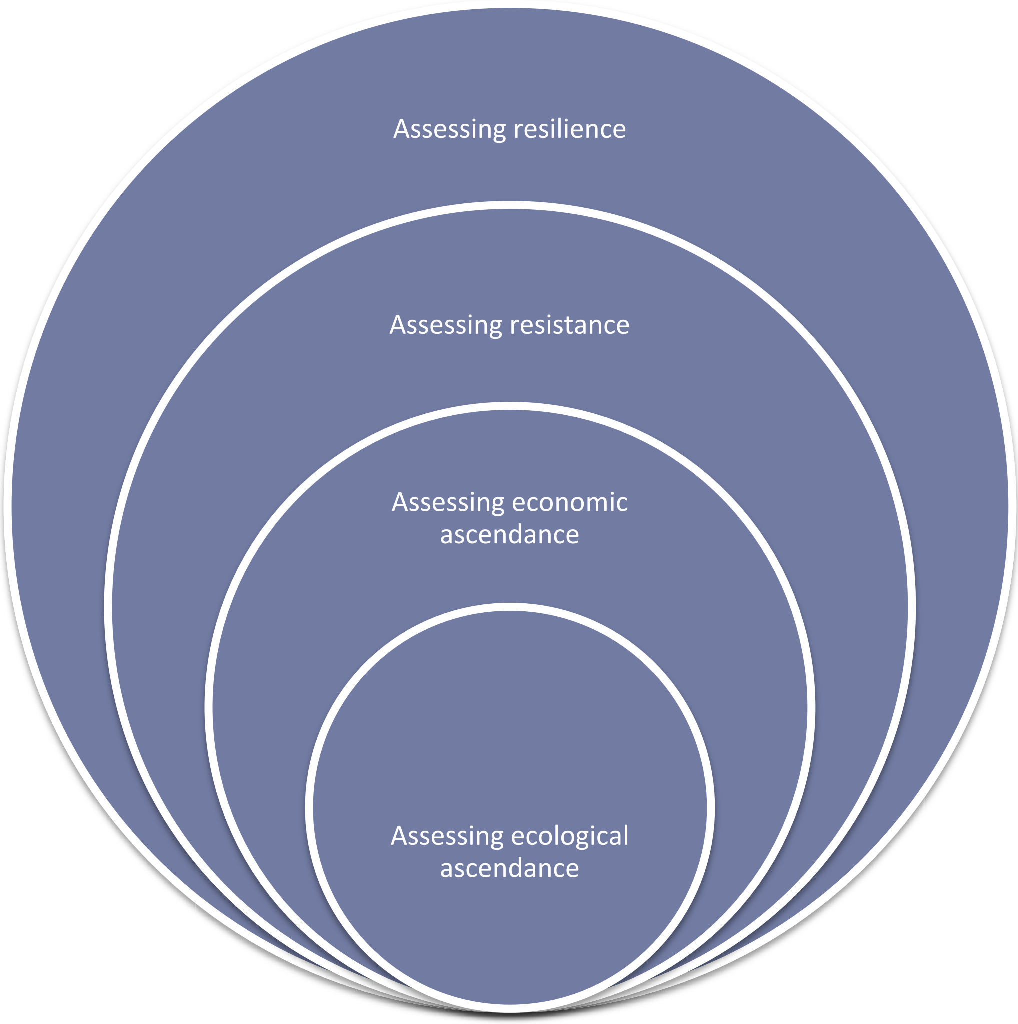

Figure 13 – Systems diagram of the relationship between resilience assessment and the other 'layers' for assessing systemic performance

Contingency analysis[20] is an extension of scenario analysis to analyse the dynamic response of systems to alternative futures (AWWA 1994). Rather than specifying strategies as a fixed set of interventions implemented at fixed points in time, strategies are specified as sets of decision logics or *policies* that implement interventions based on realistic information available at that time. The sophistication of these policies may vary from rules establishing the triggers for staged interventions (e.g. implementing water supply augmentations when reservoir storage falls below a certain level), to more nuanced contingency studies involving a collaborative assessment of how institutions would realistically respond to each scenario (e.g. by forming an expert panel and talking through how they would respond to a prolonged drought).

[20] Also known as the 'What If' method

Owing to the relatively moderate level of analytical quantitative modelling involved, contingency analysis provides a similar set of strengths to scenario analysis in that it provides the space for a qualitatively rich exploration of the range of possible futures and their responses.

However, the method suffers from the same limitations as scenario analysis in that it may become unwieldy when faced by a large number of significant uncertainties. In such situations the assessment may need to rely on increasingly strong assumptions within the decision logics or progressively confine the futures considered, potentially leading to suboptimal outcomes.

Decision analysis[21] goes a step further in applying the underlying decision logic of flexible management by identifying and quantitatively optimising a range of possible future decisions (Bellman 1952, 1957; Puterman 1994; Hobbs, Chao & Venkatesh 1997; Borison & Hamm 2005; Borison & Hamm 2008).

The analytical process of the method is extremely iterative, necessitating the use of specialist tools[22]; however the fundamental logic is relatively intuitive. Deferrable decisions characterised by a significant possible regret are first identified and specified within a decision tree or Markov decision process.[23] In addition, any system constraints are specified (e.g. environmental thresholds, minimum performance standards). Having defined the decisions and the system constraints, the probability and value (or cost) of myriad paths through the simulation sequence can then be estimated from the present to the end of the assessment period using either analytic convolution or Monte Carlo simulation, using a similar method to that described in the uncertainty analysis method. Based on the assumption that the path with the highest risk-adjusted value (or lowest risk-adjusted cost) is taken at each decision juncture[24], it is then possible to trace back through each of those paths from the end of the assessment period to the present. By tracing each path back to the current decision, the optimal risk-adjusted decision path for each alternative strategy may be

[21] Related methods include decision tree analysis, Markov decision processes, and real options analysis. Note 'decision analysis' is elsewhere used to connote a much broader set of notions associated with problem structuring etc. (Baumann, Boland & Hanemann 1997).
[22] These analyses are currently performed by linking a decision-tree program (e.g. DPL or Treeage) to the analytical model.
[23] A decision tree involves the elaboration of a tree-like graph or model of decisions and their possible outcomes, resource costs and utility. A Markov decision process instead simulates decisions and their outcomes as a discrete time stochastic control process. Tree-based decision analysis is more intuitive and mathematically simple, however for situations constituting a large number of uncertainties or decisions a full Markov process-based decision analysis may be required.
[24] A range of decision rules may be applied of which this is the most popular.

identified and simulated. The final revised probability distribution function for each alternative therefore represents the optimal path when accounting for the relative flexibility embodied in each strategy.

As distinct from contingency analysis, decision analysis quantitatively optimises the evolution of strategies using quantitative utility and probability density functions. However, much like uncertainty analysis, this additional analytical power requires a considerable additional investment of time and resources to quantitatively specify all objectives and probabilities. The method can therefore be prone to shortcuts, which either undermine the rigour of the elicitation process or narrow the scope of impacts, events and actions considered as part of the assessment. Furthermore, the most popular form of the method, so-called 'tree-based decision analysis' tends to scale poorly when faced with a very large number of uncertainties, decision junctures and/or options owing to the exponential growth of model iterations and their associated computational costs – though this limitation may be partially offset by adopting simulation-based decision analyses based on Markov decision processes.

Real options analysis (ROA) is an investment optimisation method for managing investments that may be exercised over a period of time under conditions of evolving uncertainty or learning. Though the method was originally developed in the financial sector for optimising holdings of financial stock options, it was subsequently generalised for optimising so-called 'real options' or project investment decisions.

The method manifests in a variety of forms including its closed analytic solution method (Black & Scholes 1973), the lattice method (Cox, Ross & Rubinstein 1979), the stochastic or Monte Carlo simulation method (Boyle 1977), and the decision tree or dynamic programming method (Borison & Hamm 2008). However, the most common forms of ROA, the analytic and lattice ROA methods, rely on a set of similar assumptions to portfolio analysis that are inappropriate for most real investment decisions (Borison & Hamm 2008). The remaining ROA methods, here termed the simulation and decision tree-based ROA approaches, are largely equivalent to the two forms of probabilistic decision analysis described above – the only distinction being the more pervasive use of market data to characterise uncertainties where available (e.g. using historical natural gas market data to characterise the expected future variability of natural gas prices). This thesis therefore treats ROA as largely synonymous with decision analysis.

In practice, the three methods may be usefully applied in combination. That is, decision analysis (or ROA) may be applied for all actions possibly associated with a high level of risk and/or regret, while contingency analysis may be applied for incorporating the more routine responses likely to be undertaken by institutions.

At this point it may be pertinent to highlight that the methods identified above do not in themselves overcome the difficult challenge of anticipating surprise. These methods on their own provide little support for coping with this challenge and largely still rely on the creativity and foresight of those involved. Rather, the proposed methods provide scope within the assessment process to more effectively adapt to, rather than pre-empt, those surprises. In so doing the strategies can subvert the false trade-off inherent in conventional risk assessment approaches between anticipating surprise and reducing costs.

5.5 Synthesis: an analytical process for assessing systemic performance

5.5.1 Overview

As described above, the quantitative analysis of coupled ecological-economic systems has been characterised as comprising four principal components:

- Ecological ascendance assessment, which may be variously assessed using material flow analysis and/or life cycle analysis, depending on the problem context and whether the quantification of environmental impacts is appropriate / desired.
- Economic ascendance assessment, which may be assessed using cost-effectiveness analysis and/or cost-benefit analysis, depending on the problem context and whether the quantification of objectives using monetisation is desired.
- Resistance assessment, which may be assessed using scenario analysis and/or uncertainty analysis depending on whether the quantification of uncertainties is appropriate / desired.
- Resilience assessment, which may be assessed using contingency analysis and/or decision analysis depending on whether the quantification of uncertainties is appropriate / desired.

A summary of the above considerations is provided as a decision tree in Figure 14.

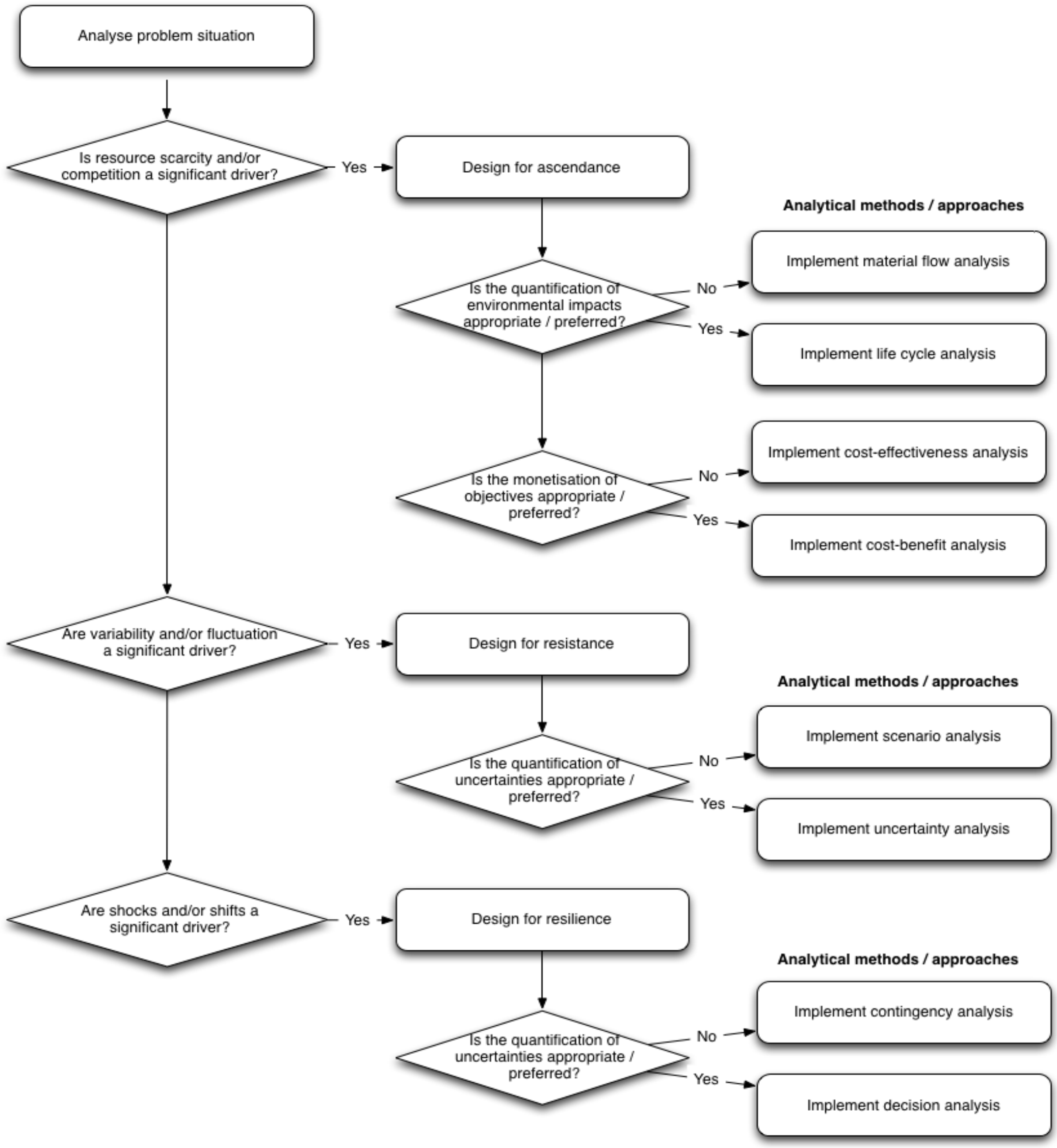

Figure 14 – Flow diagram for selecting relevant analytical methods

Furthermore, an integrated approach for assessing ecological and economic ascendance was proposed, in which economic impacts are based firmly on a model of physical flows, capacities and impacts.

Similarly, resistance assessment has been characterised as an extension of ascendance assessment for situations also characterised by variability and fluctuation, while resilience assessment has been characterised as an extension of resistance assessment for situations also characterised by shocks and shifts. The framework can therefore be depicted as nested analytical 'layers' as shown in Figure 15 below.

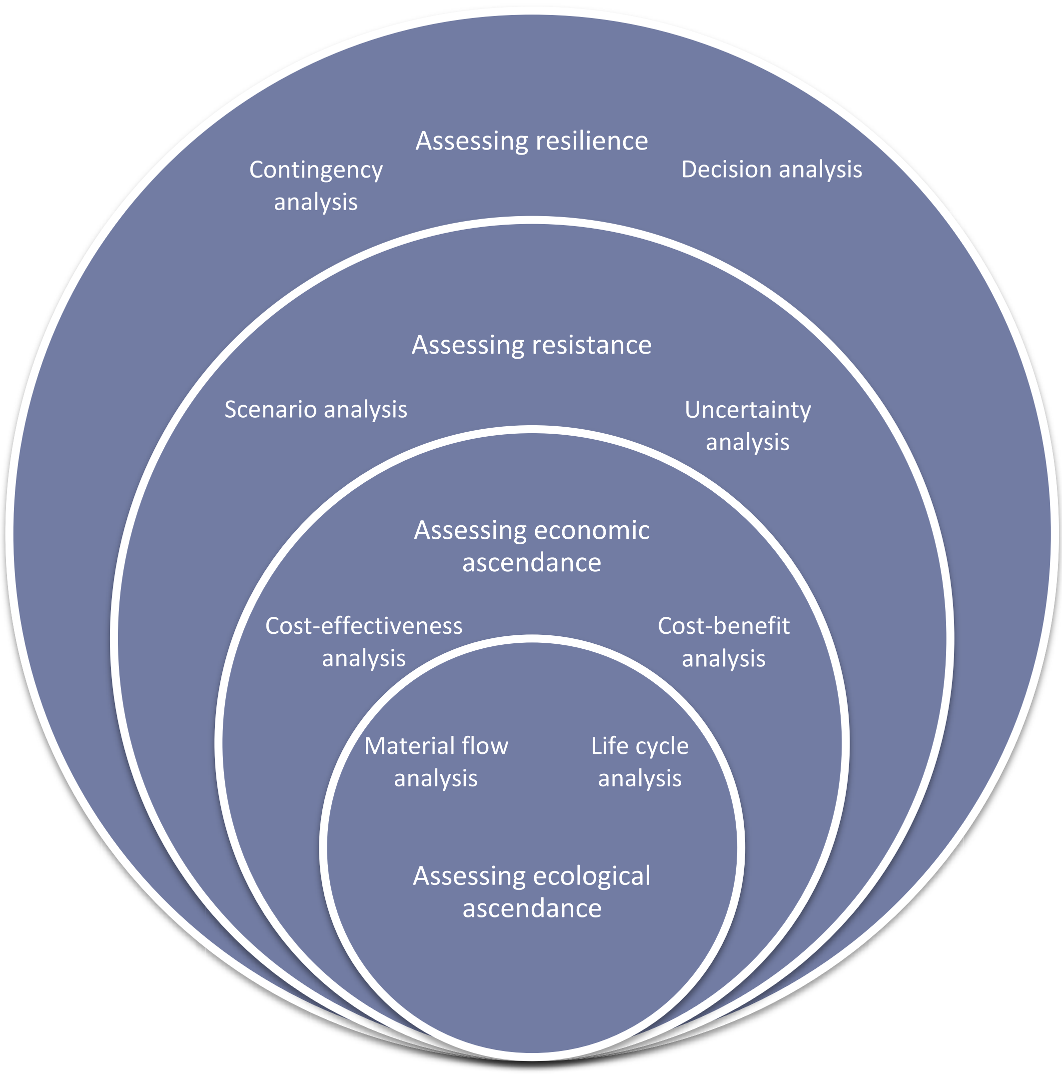

Figure 15 – Systems diagram of the different 'layers' for assessing systemic performance

5.5.2 Selecting the appropriate assessment level

The broad classes of methods outlined above should not be considered to be mutually exclusive, and processes incorporating the 'higher' analytical levels cannot be assumed to be superior for all situations. Instead, they may be seen as options for dealing with different types and levels of situational complexity.

For situations that are relatively predictable and characterised by low levels of uncertainty it may be appropriate to focus on a thorough application of ascendance assessment methods alone, possibly combined with a simple sensitivity analysis to test the robustness of the assessment to variance in the assumptions. In water and energy planning this will typically occur in situations where resistance is conferred by a larger network – that is, precinct or local area scale planning. In such situations it is often appropriate to design for any fluctuations or shocks by using a designated level of redundant capacity rather than by applying a comprehensive scenario or uncertainty analysis.

For situations characterised by significant variability and/or fluctuation, it may be appropriate to extend the analysis with scenario analysis and/or uncertainty analysis. A clear case for such an approach in a water planning context can be made when planning a water supply for a city with a high level of annual or inter-annual variability. Similarly, energy networks with a significant level of variable generation may benefit from a resistance assessment.

For situations characterised by significant shocks and shifts it may be appropriate to further extend the analysis with contingency analysis and/or decision analysis. This sort of analysis will typically benefit energy and water systems with significant exposure to socioeconomic or climate change.

5.5.3 Selecting appropriate objective treatments

Two main branches of quantitative ascendance assessment: broadly called cost-effectiveness analysis and cost-benefit analysis. Rather than considering these methods as competitors, the synthesis suggests they should instead be considered alternative objective treatments. The key question here is: What are the characteristics of the objective and how would they be best incorporated within the analysis?

If the objective is substitutable, negotiable and readily quantified in the objective function (e.g. as a cost or benefit), then the objective may be treated as a 'criterion' for subsequent optimisation alongside other criteria.

For example, consider the challenge of balancing the potentially competing objectives of adapting a water system with a changing climate, while simultaneously mitigating greenhouse emissions. If we choose to incorporate the mitigation objective in the criteria, the analyst could seek to monetise all direct and indirect emissions based on projections of greenhouse emission permit and energy prices (or a proxy thereof). During the assessment stage, all proposed strategies would therefore include their comparative mitigation performance within the specified performance criteria[25].

[25] Note that a key assumption underlying such analyses is that the adopted greenhouse emission price projections adequately reflect the real cost borne by society.

If the objective is non-substitutable, non-negotiable, or associated with thresholds of acceptability, or if quantitative optimisation is otherwise inappropriate or unacceptable, then the objective may be treated as a 'constraint' limiting the feasible systems and strategies.

If we instead apply the constraint method to the challenge above, all proposed alternative strategies could be constrained to fall below a maximum greenhouse intensity per unit of water transmitted. For those alternatives that would have otherwise fallen beyond this limit the constraint would force the inclusion of additional options to reduce greenhouse intensity (e.g. measures to reduce water pumping and heating energy).

If the assignment of both quantitative criteria and constraints is inappropriate, the objective may be incorporated within subsequent deliberation processes using a quantitative indicator or qualitative description.

If we again apply the challenge of balancing greenhouse adaptation and mitigation objectives as an example, the decision-makers could judge the monetisation or fixed limitation of greenhouse gas mitigation objectives to be inappropriate. In this circumstance they could instead establish protocols for the comparative greenhouse emissions to be reported to a deliberative assessment process alongside a suite of other considerations (including the performance criteria).

As each objective is different, this approach will typically result in a mixture of objective treatments as shown in Figure 16 below.

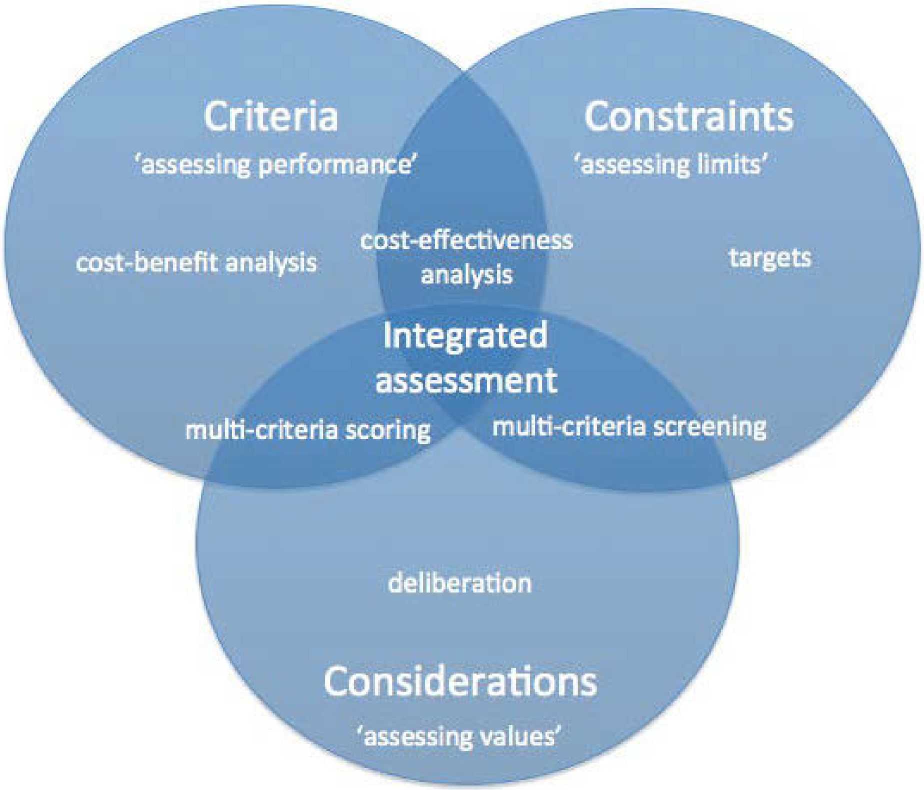

Figure 16 – Diagram depicting the integration of objective treatments

5.5.4 Selecting appropriate uncertainty treatments

A similar false dualism was observed in the various identified approaches for analysing uncertainty: so-called 'possibilistic' treatments which avoid quantifying probabilities, including scenario analysis and contingency analysis; and so-called 'probabilistic' treatments which rely on quantified probabilities, including uncertainty analysis and decision analysis.

An integrated approach to treating uncertainty would involve analysing each specific uncertainty and assessing an appropriate treatment. If the assignment and modelling of probabilities is appropriate and practical then the uncertainty may be incorporated into the uncertainty and/or decision analysis. On the other hand if the assignment of probabilities is impractical or unacceptable then the uncertainty may be incorporated into the scenario and/or contingency analysis. Taking this approach will often result in a mixed treatment of uncertainties constituting both 'probabilistic' uncertainties with quantifiable probabilities and 'possibilistic' or non-probabilistic scenario-based uncertainties as shown in Figure 17 below.

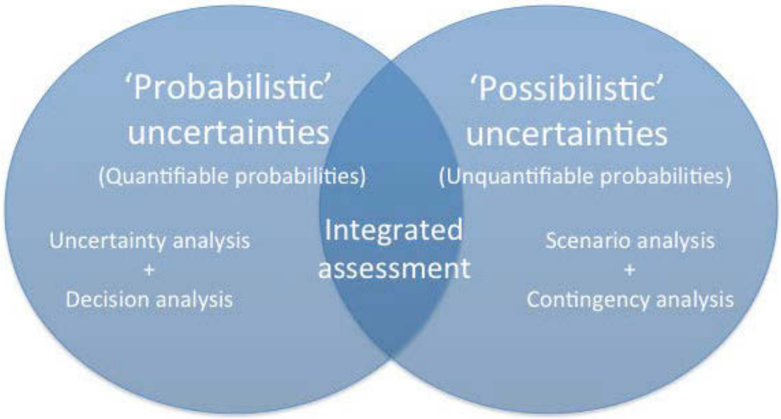

Figure 17 – Venn diagram depicting the integration of uncertainty treatments

Choosing an appropriate mix of methods that reconciles possible tensions between analytical power and complexity therefore remains the responsibility of the assessment team.

5.6 Conclusions

The above review demonstrates that there is a suite of analytical methods available for assessing the systemic performance of cities, and for analysing the strengths, limitations and effective role of each method. The review is unique in that is has attempted to remain neutral with regard to two key epistemological divisions that have been observed in the discourse – that is, whether objectives should be monetised and whether uncertainties should be quantified probabilistically. As found in the literature review in Chapter 2, existing reviews and guides have generally adopted a biased stance to these methodological judgements, leading to an unnecessary level of division in research and practice. Instead, this analysis has synthesised a set of heuristics for identifying which specific method or combination of methods may be most appropriate for a given context.

The next chapter will explore how the heuristics translate to a set of specific problem contexts, while testing the efficacy and benefits of the proposed methods in practice.

6 Applications: case studies in designing for and assessing systemic performance

6.1 Introduction

The previous chapter analysed a diverse range of analytical methods for assessing systemic performance and provided a set of heuristics for combining them into coherent assessment processes.

This chapter seeks to analyse the efficacy and benefits of the analytical methods in the context of urban water systems. More specifically, it seeks to demonstrate and validate the analytical heuristics as tools for structuring coherent and insightful assessment processes in a range of problem contexts.

To this end a series of thought experiments have been developed to highlight how different problem situations will lead to different assessment processes. The first thought experiment focuses on a relatively simple situation where the core attribute of ascendance is the primary focus and the 'higher' attributes of resistance and resilience do not warrant detailed attention. The second thought experiment extends the first by adding a significant challenge requiring more detailed consideration of the concepts and analytical methods of resistance. And the third thought experiment further extends the problem situation by adding a challenge requiring a more comprehensive analysis of resilience.

The thought experiments highlight how the conceptual and analytical frameworks lead to a different set of questions given differing problem contexts. They further highlight how the various concepts and analyses can be effectively integrated to form more integrated, affordable and robust responses, even in situations of quite severe climate change.

6.2 Positioning statement

The hypothetical case studies presented here are based on a set of similar analyses undertaken by the author during industry research projects with utilities and associated organisations across Australia. These analyses constituted confidential advice and so could not be published here but the case studies are firmly based on realistic problem situations.

The spreadsheet model applied in the analysis builds on a series of models developed by the author for a range of Australian water utilities and later the Water Services Association of Australia and the Australian National Water Commission (McKibbin, Inman & Turner 2010; McKibbin, Retamal & Turner 2011), together with research undertaken as part of an undergraduate engineering honours thesis (McKibbin 2008). A more expansive description of the spreadsheet model is provided as an appendix.

The case studies are presented in an unconventional format comprising two main parts. A series of boxes are used to present a fictional but realistic storyline providing the context and specifics of a water planning problem and explaining how the framework might relate to the day-to-day work of a water planner. A more conventional report format is used for the remainder of the text to describe the analyses performed and results generated by the author.

Although every attempt has been made to ensure the specific circumstances and parameters of the case studies are realistic, it should be noted that the analytical processes followed here diverge from real-world analyses in several respects. For instance, customer meter data and bulk meter data would usually be applied to calibrate and validate the estimates of residential and non-revenue water demand, respectively. This would not have any impact on the methodology or findings beyond minor revisions to the demand forecast. Similarly, the reservoir models could not be validated against real-world drawdown observations and the catchment models themselves would likely involve a much higher level of granularity. The catchment response is therefore considerably simplified. And finally, in real situations the estimated performance of each of the interventions would be informed by engineering estimates (in the case of network options) or statistical evaluations of past performance (in the case of demand management programs). None of these limitations impact or invalidate the central purpose of the case studies – that is, to demonstrate the practicability and value of the concepts and analyses.

6.3 Case study 1: Ascendance

Case study background

This case study is based in the fictional city of Bayton – a coastal regional city with a population of around 50,000 (or 20,000 dwellings units).

The sole water and wastewater services provider, Bayton Water, serves the city with water from a reservoir situated several kilometers inland. The reservoir has a catchment area of 24 square kilometres and a capacity of 25 gigalitres.

The wastewater system, though less extensive in coverage, comprises a tertiary treatment plant that returns treated wastewater to Francis Bay, a thriving estuary serving the town's local fishing industry. Properties not served by the gravity sewer network are largely served by conventional septic tank systems owned and operated by the property holders.

Bayton Water is exploring a range of water supply options to meet its growing population while simultaneously extending sewer services to un-served properties.

Bayton City Council is emphatic that the chosen strategy should be least cost and reflect the cutting edge of material resource efficiency and sustainability, so the analytical team thought they'd try out an analytical framework that they discovered at a recent conference.

The framework identified three 'attributes' or modes of water resource planning problems. The first attribute, which was termed 'ascendance', sounded broadly like a new conceptual framing for their core concerns for achieving cost-effectiveness and sustainability. The second attribute, which they termed 'resistance', seemed to correspond to their various concerns around maintaining reliability. The third attribute, 'resilience', seemed to correspond with their various concerns around managing extreme droughts and other contingencies.

Owing to the emphasis on sustainability, the team decided to at least initially focus on the concepts and analysis of ascendance.

6.3.1 Establishing the objectives

The framework delineated three core approaches for specifying 'ascendance' or resource management performance objectives:

- constraint objectives, which involve incorporating aims as targets or minimum thresholds
- criteria objectives, which involve incorporating aims by assigning a monetary or other quantitative measure of value
- consideration objectives, which involve incorporating aims by providing quantitative or qualitative descriptions of the impacts for subsequent deliberation.

(see Section 5.5.3)

The analytical team didn't have the resources or the need to undertake a non-market valuation study to quantify the economic benefits of water service provision. They therefore decided to adopt a constraint-driven approach for the utility's core water service objectives whereby all feasible alternatives must meet a minimum level of service.

Similarly the study didn't have the resources to undertake detailed ecological and economic modelling of the economic impacts on Francis Bay, so the environmental objectives were similarly incorporated as constraints limiting the range of feasible strategies.

The objective of the study was specified as:

- to provide sufficient water to withstand the full historical record of weather under normal potable water demands.

The subsidiary objectives were specified as:

- Wastewater disposed to the Bay must be treated to tertiary standard (i.e. including nutrient removal).
- Subject to the above objectives, water services should be provided at a minimal economic cost, expressed as the net of costs and benefits borne by all affected stakeholders (excluding social and ecological externalities).

6.3.2 Scoping the system

The analytical team then set about defining the scope of the study. The framework delineated two key system boundaries for consideration:

- the ecological system boundary, which describes the physical resource flows included in the assessment
- the economic system boundary, which describes the financial resource flows and any other non-financial impacts included in the assessment

(See Section 5.2)

The ecological and economic system boundaries will therefore necessarily differ, as they deal with qualitatively different entities and resource flows.

Although the analytical team hadn't explicitly defined system boundaries in this way in the past, they realised that the city's water planning studies had previously applied a quite narrow system boundary relative to that recommended by the framework.

For instance, in the past their 'ecological system boundary' typically only focussed either on the potable water system or the wastewater system. They also typically ignored consideration of energy consumed or nutrients disposed to the water system.

Similarly, they realised that their 'economic system boundary' had implicitly ignored the costs and benefits borne by the customer by, for instance, ignoring the costs to households of purchasing rainwater tanks. Although this simplified the analysis considerably, the analytical team realised that they could be missing important interactions between their various sustainability objectives and attempted to apply a more comprehensive approach.

Consistent with this more holistic approach the physical or ecological system boundary was drawn to include both the potable water system and the wastewater system. The system boundary was extended beyond water and wastewater volumes alone to include loads of nitrogen and phosphorus. Any energy associated with the water and wastewater systems was also considered, including energy consumed in the water treatment, distribution, use, wastewater collection and treatment.

The institutional or economic system boundary was also explicitly extended beyond Bayton Water to also include all households and businesses served by Bayton Water, and any other partner institutions. They recognised that any costs or benefits excluded from this monetary assessment should be explicitly highlighted. This enabled the different social values and differing distributions of costs and benefits associated with different options to be assessed transparently.

6.3.3 Modelling the system

> The analytical team then set about constructing an analytical model to analyse the existing supply-demand balance. Demand was historically modelled using a statistical regression of the historical bulk water consumed as a function of daily rainfall and evaporation, combined with some additional explanatory variables capturing longer-term trends around population, price and income. The water supply capacity of Bayton was modelled using a separate catchment model that established an annual maximum sustainable yield subject to existing operational settings and restrictions.
>
> In addition to the more conventional statistical modelling method applied, the analytical framework highlighted the benefits of applying dynamical or 'bottom up' demand modelling methods as a means to better understand the efficiency and intensity of resource use. The analytical team therefore sought to construct an 'end use model' to better understand the drivers of water demand and ultimately any opportunities for improved end use efficiency.

The first step of the modelling exercise involved developing 'bottom up' estimates of potable water demand for the key residential appliances. This involved developing a quantitative description of three broad appliance characteristics as prescribed by the end-use modelling approach (Baumann, Boland & Hanemann 1997).

resource consumption = stock x behaviour x technology

The 'behaviour' or the usage characteristics of each appliance, were specified using a suite of key behavioural parameters drawn from surveys and end-use measurement studies in Australia (Loh & Coghlan 2003; Roberts 2004, 2005; EES 2006; ABS 2007; ABS 2008) and validated by several end-use modelling projects in capital cities across Australia. The specified parameters were assumed to remain fixed into the future and included typical shower frequency and duration, clothes washing frequency, and dishwashing frequency.

The 'technology' or the intensity of resource consumption per unit of activity, included the volumetric water consumed / wastewater generated by different appliances, the nutrients disposed to the wastewater system, water temperatures and energy consumed per activity. These parameters were based on end-use measurement studies and sales tracking studies undertaken in Australia (EES 2006). In each example the baseline assumed that no new technologies were introduced and that the existing appliance sales shares would continue unchanged.

The 'stock' or the total number of each appliance was modelled using a cohort component modelling[26] approach (Muth 1973; Greene, Meddeb & Liu 1986; Riedy 2003). This involved first estimating the total number of appliances in the region based on observed appliance penetration or saturation figures and multiplying this by the number of available households. This total number of appliances was then input as the annual number of appliance sales in the first year of the model (which in this case was hindcasted to 1960), while any growth in the number of appliances was input to the model as a time series of new appliance sales.

The fate of each annual 'cohort' of appliance sales was then modelled to simulate the turnover of appliances over time, and therefore the rate at which changes in water efficiency will impact overall water consumption. This provides a basis for estimating the impacts of water efficiency programs such as regulations, rebates and information programs.

The replacement of appliances was modelled as a lognormal decay process, with mean appliance lifetime and shape parameters determined from observed appliance replacement data where possible.

[26] Cohort component modelling is sometimes termed vintage stock modelling

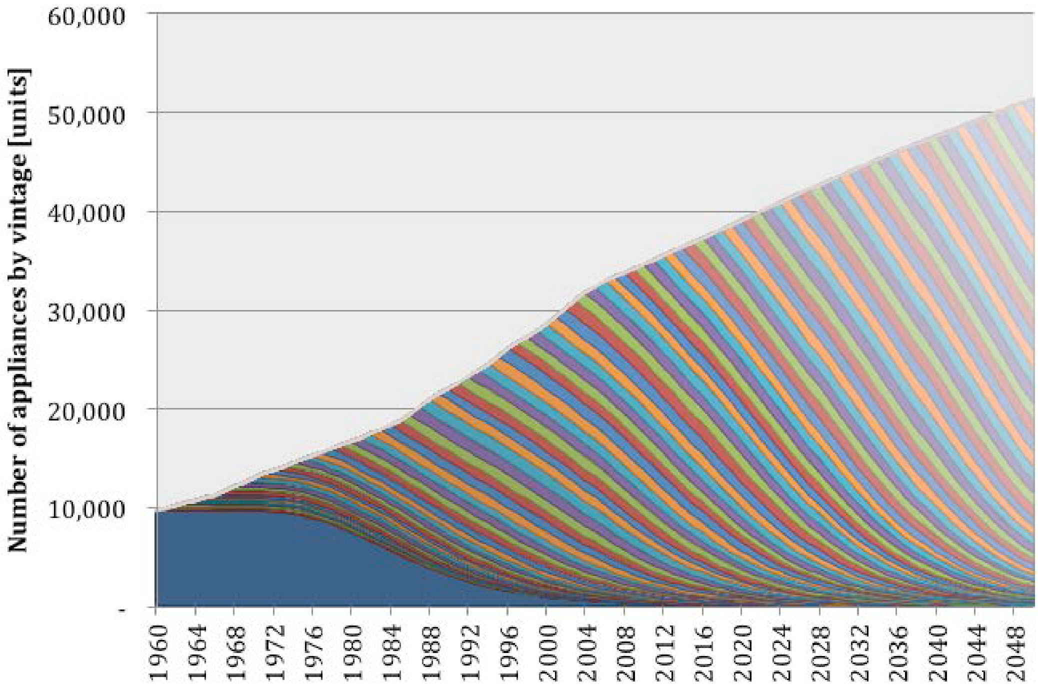

Figure 18 – Illustrative chart of modelled appliance cohort decay over time

The chart above illustrates the underlying mechanics of the appliance stock models. The bands of colour represent cohorts of appliances purchased each year – that is, the annual increase in the total number of appliances plus the number of older appliances that are replaced in that year. The chart also demonstrates why the model needs to commence 50 years prior to the assessment period, as otherwise the cohort of appliances sold in the initial year (marked in blue) would be spuriously dominant in the stock mix.[27]

[27] An alternative approach would be to apply a sample-based survey of households to interpret the age distribution of appliances. This would remove the need for historical demographic data.

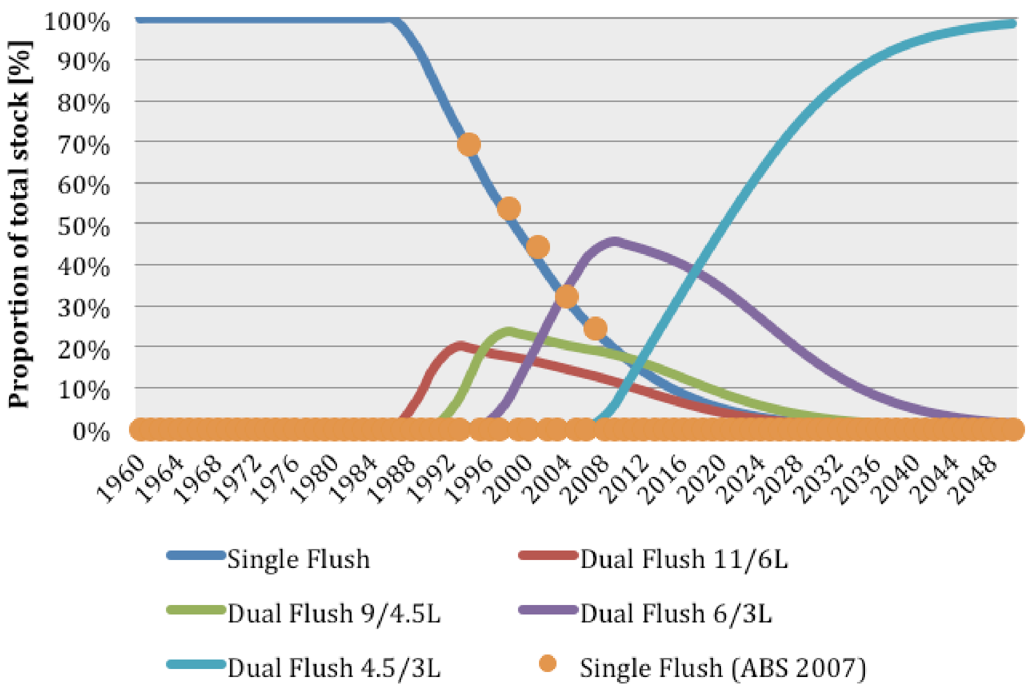

Figure 19 – Illustrative chart of modelled annual toilet stock composition by appliance type

Figure 19 depicts the model results for the toilet appliance model developed by the author and applied in this case study. Each curve represents the growth and subsequent replacement of a new toilet technology, beginning with single flush toilets, and then showing increasingly efficient dual flush toilet models. The rate of replacement, described by a lognormal decay process, was fitted to the observed rate of replacement of single flush models following their replacement in 1984.

The next step involved elaborating a bottom-up or dynamical relationship between the prevailing weather conditions and the water consumed by outdoor appliances such as pools, lawns and gardens. This was achieved by constructing several water balance or 'bucket models' of irrigation and pool demand. That is, the pool or soil mass was modelled as a water storage of fixed capacity with rainfall as the primary input and evaporation / evapotranspiration as the primary output, and any shortage of water was made up with irrigation. This method was first demonstrated for demand forecasting purposes by the author for the City of Wagga Wagga (McKibbin, Retamal & Turner 2011), and has since been validated in consulting projects undertaken by the author in several cities across Australia. Note however that the approach has not as yet been applied for uncertainty analyses of climate variables such as the analysis presented in the case study below.

Figure 20 provides the outputs of this model for a typical residential property based on historical climate data.

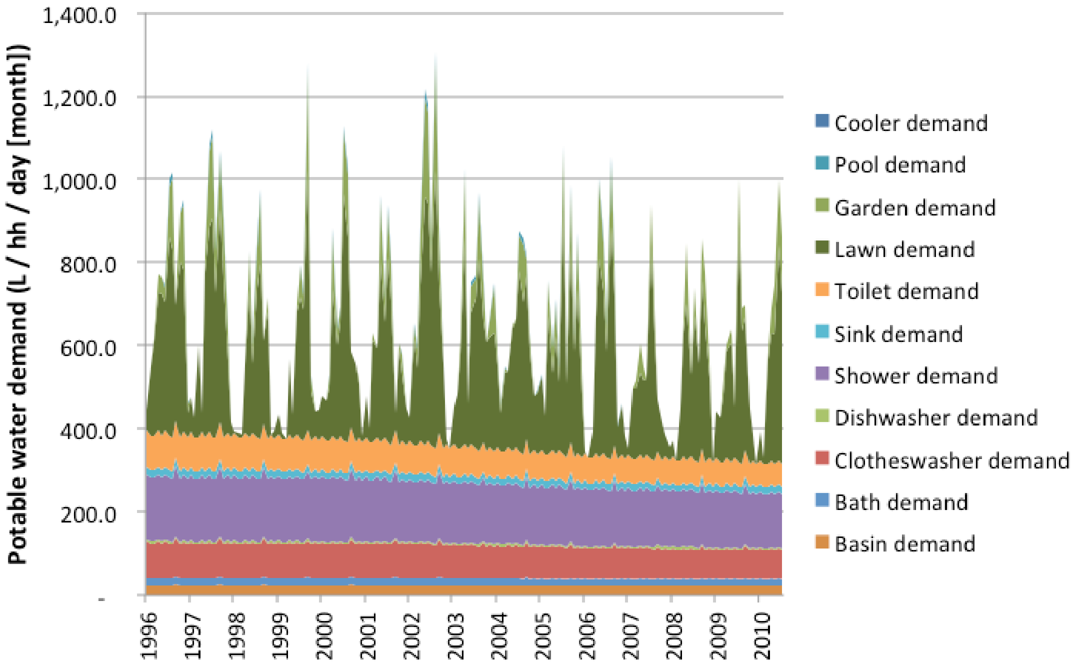

Figure 20 – Modelled annual household demand by end use (excludes non-residential demands)

The chart demonstrates two dynamics that the model seeks to capture with respect to residential demand. Firstly, the indoor end uses demonstrate a long-term trend toward reduced demand driven by improved technology performance over time, particularly in clothes washers, showers and toilets. Secondly, the chart shows how the various outdoor end uses including lawns, gardens and pools fluctuate according to variations in rainfall, temperature and evapotranspiration rates.

Industrial and commercial loads were analysed using a much more simple approach owing to their relative heterogeneity and lower representation as a share of overall loads. This involved calculating a simple regression of demand as a function of population and then extrapolating that function with residential population projections.

The modelled water demand by end use in the base year is shown in Figure 21.

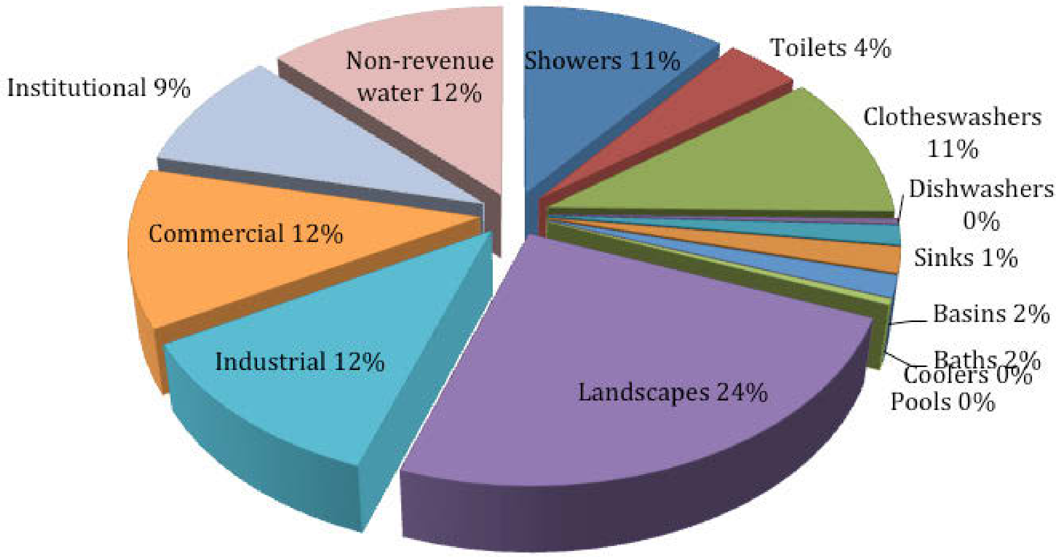

Figure 21 – Baseline water demand composition by end use

This 'current state' model was then projected into the future using projected population and household forecasts for the town. The population growth forecast was then linked to non-residential demand by assuming commercial and industrial demand would grow linearly with population, yielding the demand forecast shown in Figure 22.

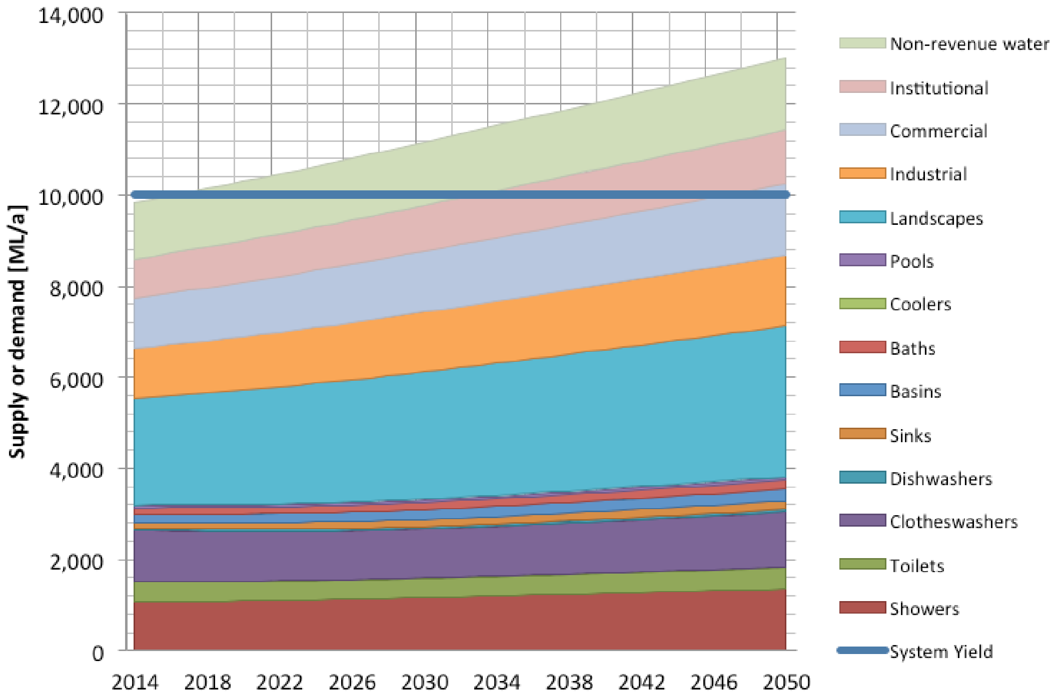

Figure 22 - Modelled supply-demand balance

6.3.4 Identifying the options

The analytical team's next challenge was to identify and model a suite of options for meeting the study objectives. The conceptual framework identified two conceptual mechanisms or 'templates' for improving the performance of systems subject to resource challenges:

- functional intensity
- structural integrity

Delving deeper into the functional intensity mechanism, the framework described a much broader range of mechanisms for improving the 'ascendance' of a system:

- resource expansion: resources that were previously unexploited may be harvested
- resource efficiency: existing resource flows may be more efficiently applied
- resource recirculation: existing waste flows may be recycled.

Historically the water utility had predominantly focussed on the construction of supply infrastructure alone or 'resource expansion' in the terms of the framework. The framework therefore proposed a significantly wider scope of options than had typically been considered previously. The analytical team figured this would align well with the council's request for a more innovative sustainability response. The team therefore decided to use the three option categories to structure a stakeholder option identification process to develop a shortlist of options for detailed consideration.

The structural integrity mechanism highlighted additional approaches to improving resource performance:

- network link configuration, or the optimisation of distribution and collection network capacities and topologies for resource efficiency
- network component configuration, or the optimisation of water supply, consumption, and wastewater treatment component positioning to maximise network efficiency
- network load reduction, that is, capturing the network benefits of efficiency and 'tight recirculation' or local recycling close to the source.

While the utility had a pretty good handle on the network configuration problem, they hadn't previously assessed the network impacts of component positioning decisions in detail. On consideration the team realised that operational benefits could arise from efficiency and recirculation options in terms of reduced network costs, and so they decided to try to incorporate them into the assessment. Taking this idea a step further they made a decision to consider local efficiency and recycling options as a practical alternative to extending the wastewater network, leading to a range of creative options.

The first set of options comprised two more traditional supply side options:

- reservoir augmentation – increase the level of storage provided by the existing reservoir by 50%
- seawater desalination – install a 3 ML/d seawater desalination plant.

Two options were identified for improving end-use efficiency:

- indoor efficiency – provide a swap scheme to replace existing inefficient showerheads with efficient alternatives
- outdoor efficiency – introduce rebate incentives and a marketing program to encourage residents to replace European gardens with hardy native plants in addition to using efficient watering equipment.

Two options were identified for recycling resources:

- greywater recycling – promote low tech household recycling of greywater for garden irrigation and toilet flushing
- decentralised recycling – provide advanced wastewater treatment and third pipe reticulation to all new developments to service non-potable demand.

Two new options were identified for harvesting previously unexploited water flows:

- rainwater harvesting – provide rebate to install household rainwater tanks
- stormwater harvesting – install stormwater harvesting systems at several strategically identified across the network.

A series of option assessment spreadsheets were developed to identify the physical and economic impacts associated with each option. For the technical water supply options this involved estimating the annual water yield, capital cost and operating costs associated with each measure, together with an estimate of the typical energy consumed per unit of water generated.

For the efficiency and source substitution measures this involved firstly estimating the likely number of properties targeted by the program, their likely participation rates as a percentage of the target properties, the water savings per participating household, and the program costs per participating household (both to the household and the utility).

6.3.5 Assess the strategies

The results for each option were combined into a unit cost curve of cumulative option yield or 'supply curve' (Meier 1982) depicting the relative yield and cost-effectiveness of each option as shown in Figure 23.

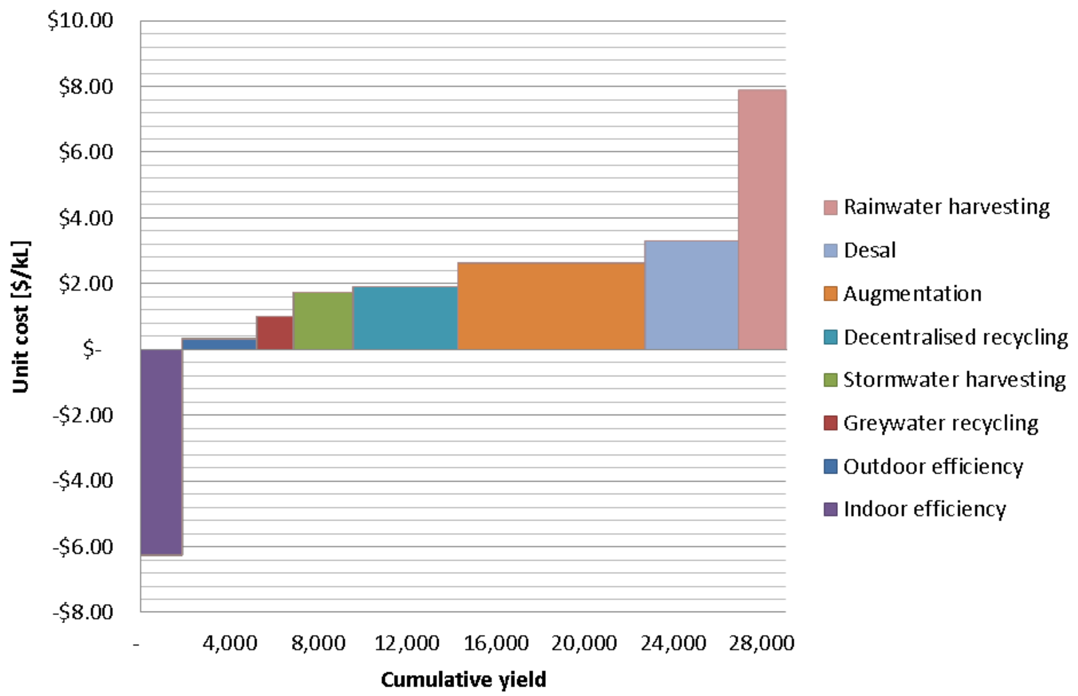

Figure 23 - Cost curve of cumulative option yield

The width of each bar represents the yield from that option in the target year, while the horizontal axis represents the yield of the option portfolio in the target year as each successive option is added. The vertical axis represents the cost-effectiveness of each option expressed in dollars per kilolitre supplied or avoided over the life of the option – both discounted to be expressed as present values (Fane, Robinson & White 2003). The options are sorted in order of decreasing cost-effectiveness and demonstrate the broad priority of the options if cost-effectiveness was the sole selection criterion.

Epilogue

The results of the analysis were provided as a spreadsheet model and a full report was presented to the board. A summary was subsequently embedded within a stakeholder deliberation process to determine the preferred water resource mix.

The deliberations also considered a range of intangible considerations. For instance, community consultations and deliberations revealed a strong preference for options that substantially improved the 'liveability' of the city through, for instance, improvements to green space. These co-benefits were explicitly excluded from the quantitative analysis.

The resulting strategy therefore didn't necessarily align with the optimal 'least cost' portfolio as prioritised by the quantitative modelling, but was rather a combination of the quantitative analysis alongside more qualitative considerations.

6.3.6 Discussion

The case study demonstrated the application of the concepts of ascendance for the purposes of designing urban water systems. The mechanism of functional vitality highlighted the breadth of options for meeting the city's water supply needs, including water efficiency programs, water recycling schemes, or through harvesting new water steams that are not otherwise captured such as rainwater and stormwater. The mechanism of structural integrity focussed on the network connections associated with those schemes. For instance, instead of returning wastewater to wastewater treatment plants, providing high levels of treatment and then returning water through expensive third pipe networks, the mechanism highlight the benefits of decentralised greywater recycling.

The case study also combined several analytical methods recommended by the analytical review. The key pillars of the approach were end-use modelling, cohort component modelling, and cost-effectiveness analysis.

The end-use modelling approach provides a model of demand from the 'bottom up'. As distinct from conventional demand forecasting approaches that apply econometric regressions, the forecast does not assume stationary relationships between demand and system variables such as weather, income and price. Instead, the forecast is derived from detailed physical mechanics. This makes end-use modelling more suitable for longer-term forecasts where the stationarity assumption is inappropriate. Furthermore, the underlying models may be altered to provide estimates of the likely savings from demand management and source substitution initiatives.

Cohort component appliance stock modelling was also extensively applied to provide long-term estimates of the impact of market and regulation-driven appliance stock changes. Although such effects have a negligible impact over short time frames of three years, they become a dominant driver of demand changes over the typical period of water system investments.

Cost-effectiveness analysis was also applied to provide an integrated assessment of the water supplied or saved, and the financial costs and benefits attributable to each option. The key benefit of this approach is the ability to provide a balanced assessment of the options available, whether they involve conventional supply side options (e.g. reservoir augmentations) or demand-side options (e.g. efficient appliances). Furthermore, by embedding key objectives as constraints, the approach obviated the need for expensive and often contentious non-market valuation studies necessary for a comprehensive cost-benefit analysis.

The analysis also adopted a significantly extended scope of physical flows with respect to conventional water resource planning studies. For instance, by quantifying the energy savings associated with the indoor efficiency programs it was possible to capture the significant benefits arising from reduced energy bills associated with avoided water heating. Utility project assessments typically exclude these avoided water heating costs, despite providing considerable financial benefits to households. Similarly, by quantifying the flows of nitrogen and phosphorus, the costs of those flows could be more directly quantified in terms of the treatment requirements at wastewater treatment plants. Taken inversely, the avoided costs of nutrient management and recycling options were effectively realised, providing a strong economic justification for a more ecologically sustainable approach.

However, by excluding consideration of the concepts and analyses of resistance and resilience the case study had several limitations.

Firstly, because it assessing options on a stand-alone basis the analysis was unable to effectively account for interactions between options and existing sources or interactions between the options comprising the desired portfolio. This means that the performance of the water system may be significantly overestimated or underestimated in situations of variability and fluctuation.

Secondly, by fixing options to a fixed schedule the analysis effectively assumes away the managerial flexibility available to the water utility to adaptively respond to the supply-demand balance shortfalls if and when they arise, potentially leading to avoidable sunk costs. For example, it may be the case that demand does not in fact grow as forecast and instead falls appreciably. In such circumstances it would be prudent to defer the augmentation of supply infrastructure, however the analyses performed so far ignore this flexibility.

The following case studies explore how these limitations may be addressed.

6.4 Case study 2: Ascendance and resistance

Case study background

After a recent drought experienced in the region, Bayton Municipal Water decided to extend its assessment process to analyse the robustness of the water supply to variability in greater detail. There was a great deal of talk in the water industry about so-called 'diversified portfolios' but there wasn't much clarity about what this meant on the ground. They also needed analysis to demonstrate that there was value to the customer both in terms of affordability and service reliability.

The analytical team therefore set about extending the analytical process to better analyse the impact of variability and the relative robustness of different water resource portfolios. On reviewing the framework they realised their specific challenge aligned well with what the framework described as 'resistance' so they delved a little more deeply into its associated concepts and analytical methods.

6.4.1 Establishing the objectives

At the outset the analytical team realised that there would necessarily need to be a shift in how the level of service objectives were framed to accommodate the extended analysis.

The framework identified two broad analytical approaches for expressing objectives related to withstanding variability and fluctuation:

- a 'possibilistic approach' whereby plausible scenarios are constructed and tested against the analytical model
- a 'probabilistic approach' whereby probabilities are assigned to the specific variable factors and simulated using a stochastic modeling approach.

(See Section 5.5.4)

Using the analytical framework as a heuristic tool, the team opted for a probabilistic approach for two reasons:

- extensive historical weather data was available for describing the probability distribution of the weather parameters
- the range of probable futures could be combined quantitatively into consolidated metrics, thereby simplifying the subsequent decision-making process.

This last reason was a key benefit. The output of a probabilistic analysis is a cumulative probability density function that can be readily summarised as a reliability metric. This in turn enables the performance of the system to be benchmarked against clear quantitative indicators.

Consistent with the extension of the study aims, the objectives of the assessment were modified to be consistent with the desired probabilistic approach. In the place of the previous deterministic objective the water service objective was re-stated probabilistically as being the provision of sufficient water to meet unrestricted daily demand 95% of the time. Expressed more specifically the expected value or mean frequency of restrictions should be equal to or less than 0.05.

6.4.2 Modelling the system

While the scope of the previous definition was quite comprehensive, the connections between the reservoir yield, the various components of water demand, and the yields associated with options were all specified as isolated models. Although this approach was previously sufficient, it now represented a limitation as it could not adequately represent the correlations in response to the various model components subject to variability and fluctuation.

Consistent with the revised model approach, the various components of the model were then combined to form an integrated analytical model. Firstly, this involved revising the outdoor demand model components and the rain tank models so they all depended on a consistent set of weather parameters.

Secondly, a 'bucket' model similar to that applied for the irrigation models was constructed to provide estimates of runoff generated across the reservoir catchment surface. This involved removing the irrigation component and instead inputting all overflow from the soil storages as runoff to a subsequent reservoir water balance model. The output of this reservoir storage was the total bulk water demand, specified as a total of all residential, industrial, commercial and institutional and non-revenue water demand. The result is a running time series of daily reservoir storage as shown in Figure 24.

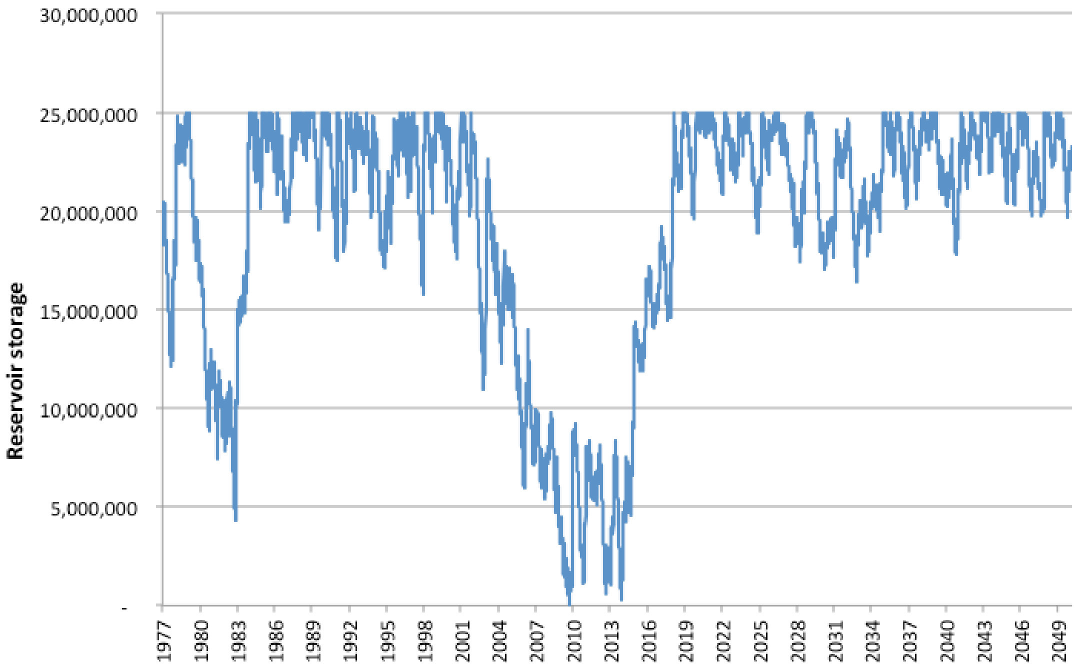

Figure 24 – Modelled reservoir storage water balance for a single simulation run

Thirdly, a weather generator was constructed to provide a more comprehensive picture of the variability of the system. This involved calibrating a stochastic Markov process to the full available record of local meteorological measurements (60 years of daily records) using an approach consistent with that proposed by the ClimGen team at Washington State University (Nelson 2002). The weather generator was then used to generate weather sequences in a Monte Carlo-style stochastic simulation as shown in Figure 19 below.

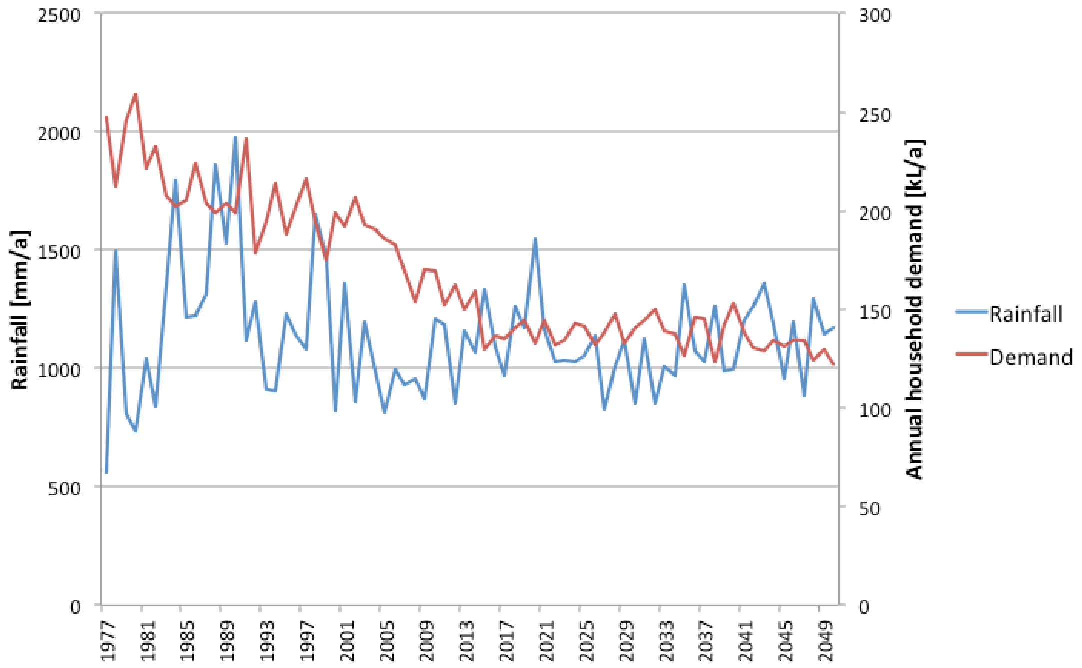

Figure 25 – Comparison of historical rainfall to a synthetically generated rainfall sequence

It should be noted that this weather generator has several known limitations. While it adequately reflects the variance in monthly mean rainfall it fails to effectively capture inter-annually variable weather processes such as the El Nino / La Nina southern oscillation, which are significant drivers of the historical weather series shown above.

The synthetic weather data was then applied consistently in the reservoir model and the various outdoor demand models to ensure all the components of the system responded coherently with the weather time series. In so doing, the covariance of reservoir yields and outdoor demands could be effectively analysed.

After specifying the weather generator, the resulting model was iterated 100 times for the entire synthetic weather record over the full simulation period of daily time steps to 2050. For each simulation, a count was recorded of the number of days with total reservoir storage below 30% (the specified trigger for an emergency or severe restriction event).

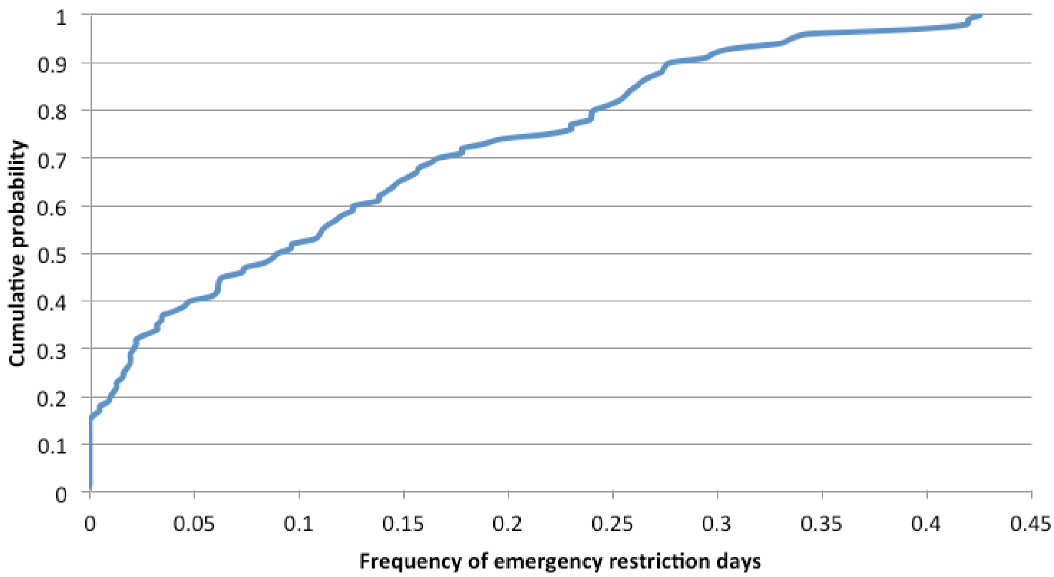

Figure 26 – Cumulative probability distribution for frequency of emergency restriction days

The results were depicted as a cumulative probability distribution function of the frequency of water restrictions as shown in Figure 26 above. The expected frequency of emergency restriction days is 12.4%, which is significantly above the target maximum frequency of 5%. The analysis therefore indicates that the current system has an unacceptable risk of emergency restriction levels occurring, necessitating a consideration of additional measures.

6.4.3 Identifying the portfolios

The conceptual framework identified two key conceptual mechanisms of templates for improving the performance of systems subject to variability and fluctuation:

- functional diversity
- structural complexity.

Delving deeper, the functional diversity mechanism described several different types of diversification:

- ‘resource diversification’, which for the urban water context implies exploiting categorically different water resources
- ‘spatial diversification’, which for the urban water context implies exploiting water resources with a different catchment region or size
- ‘temporal diversification’, which for the urban water context implies exploiting water resources sensitive to different time periods (e.g. they have different response times, initial losses, time lags etc.).

The existing option portfolio already had a strong alignment with these mechanisms. For instance, the desalination option was a clear example of ‘resource diversification’. Similarly, the stormwater and rainwater harvesting options were clear examples of both ‘spatial diversification’ and ‘temporal diversification’ as defined in the conceptual framework.

However, beyond highlighting prospective options, the concepts emphasised the importance of incorporating these diversification effects in the way the option models were developed. For instance, the diversification benefits of rainwater and stormwater options were unlikely to be fully realised unless the option models adequately incorporated their relatively weak correlated responses with the principal storage. The analytical framework offered two main approaches for modelling correlations:

- ‘statistical modelling’, which involves assigning statistical correlations between the option yields from the ‘top down’
- ‘dynamical modelling’, which involves elaborating a mechanistic description of their interactions from the ‘bottom up’ through an integrated, detailed model.

Although statistical modelling would be a convenient shortcut for simulating the correlations, no existing data was available for establishing the statistical correlations. In the absence of such data the team opted for a dynamical modelling approach. That is, all interrelated option models had to be connected to the underlying mechanics that connect them, which in this case implied connecting all option models to the same synthetic weather series.

A similar process of integrating the model was then undertaken with the various option spreadsheets. That is, the various option models were directly connected to the stochastic parameters in the baseline analysis to ensure they responded appropriately to the Monte Carlo simulation.

The interactions among the options were then identified and modelled in a similar process to that applied for the baseline forecast components. For instance, care was taken to ensure that source substitution measures such as rainfall harvesting and decentralised recycling adequately reflected any changes in underlying end-use demand if implemented in combination with indoor and outdoor efficiency measures. By adopting this approach it was possible to effectively analyse the correlation among option yields.

Instead of emphasising the development of individual options as in the previous case study, the resistance approach emphasises the role of suites of options or 'portfolios'.

Taking a closer look at structural complexity, the mechanism highlights the benefits of a nested network configuration whereby lower 'levels' of the network (e.g. an individual household) are supported by, and support, progressively larger network levels (e.g. cluster, neighborhood, suburb).

An interesting concept emerged from the translation of the structural complexity mechanism into water systems design. While direct household greywater recycling systems represent an affordable means to provide irrigation water, the greywater generated is often surplus to the needs of individual properties. The analysts therefore explored a portfolio whereby households were connected by a low-pressure greywater network to allow greywater to be shared between properties and public spaces. Taking a step further this greywater network could be readily integrated into a broader decentralised recycling scheme to allow greywater to be either 'upcycled' to support the broader potable water supply network or treated and safely disposed to waterways. A similar principle was applied to rainwater harvesting. That is, instead of disposing of it in the stormwater network, excess rainwater could be shared with adjacent households directly, or with other households in the neighbourhood via the low-pressure greywater network.

A suite of alternative combinations of options were identified, with each option sequentially added in order of its risk-adjusted cost-effectiveness, including interactions with the existing portfolio[28]. The combinations identified were:

1. Indoor efficiency
2. Indoor efficiency + outdoor efficiency
3. Indoor efficiency + outdoor efficiency + greywater

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[28] Note that ideally the analyst would test all possible combinations of options (i.e. all 256 possible option portfolios). However this would have involved a total calculation time of approximately 71 hours using a spreadsheet-based model on a high performance computer. The process of sequentially adding options to the portfolio based on their risk-adjusted least cost option therefore represented a compromise.

4. Indoor efficiency + outdoor efficiency + greywater + stormwater
5. Indoor efficiency + outdoor efficiency + greywater + stormwater + decentralised recycling
6. Indoor efficiency + outdoor efficiency + greywater + stormwater + decentralised recycling + rainwater
7. Indoor efficiency + outdoor efficiency + greywater + stormwater + centralised recycling + rainwater + desalination

6.4.4 Assessing the portfolios

The stochastic simulation runs of 100 simulations were then repeated sequentially with each of the portfolios activated and the frequency of emergency reservoir levels and costs recorded for each run.

The results for each portfolio were then plotted against two axes: expected frequency of restrictions and expected cost expressed as a net present value (as shown in Figure 21). Owing to the logic by which the portfolios were formed (that is adding options in sequence of increasing cost, taking account of correlation), the portfolios form a curve beginning at the lower left with the lowest cost (or highest benefit when costs are negative) but low reliability through progressively increasing cost and reliability to the upper right corner with highest cost (or lowest benefit) and highest reliability.

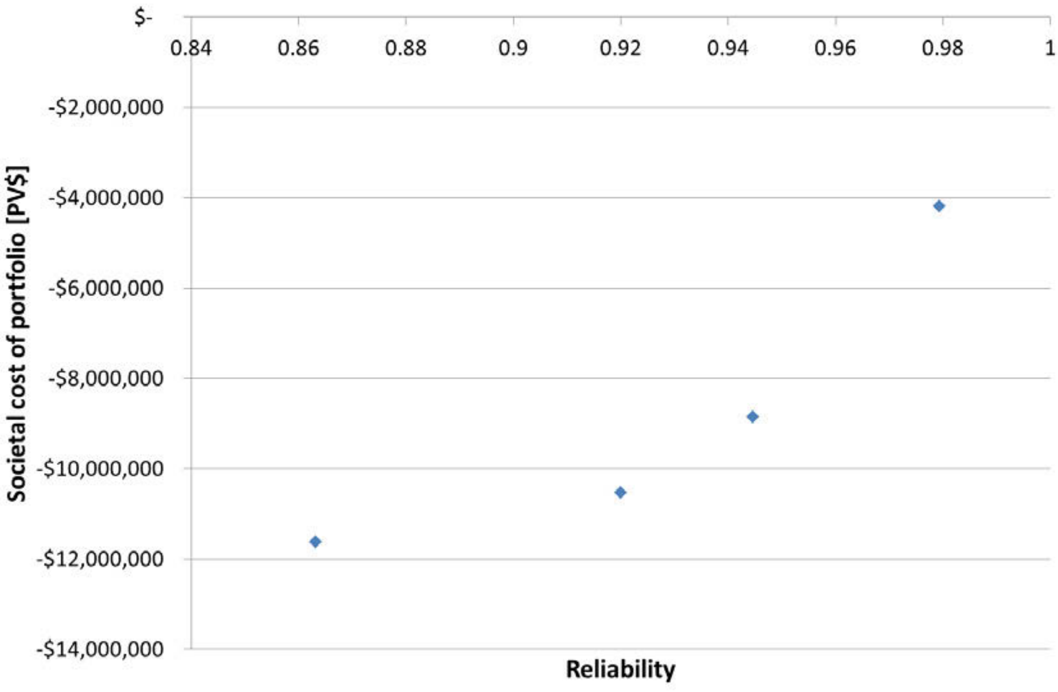

Figure 27 – Risk-cost frontier curve

This curve shape is broadly consistent with what is termed an optimal risk-cost frontier curve in modern portfolio theory. The key difference is that a conventional risk-cost frontier curve in financial theory is a continuous curve whereas the lumpy nature of the water resource portfolio means that the curve is constrained to a series of discrete points.[29]

Using this curve, the decision-maker can readily trade off improved reliability against cost-effectiveness. For example, taking the example of the 0.95 reliability threshold, Portfolio 3 represents the least-cost portfolio for realising that target, taking into account the interactions across the entire option portfolio.

> ***Epilogue***
>
> The analytical outputs were subsequently provided to a stakeholder forum to provide a readily understandable means to identify the optimal water resource portfolios for a given desired level of service reliability. The analytical outputs enabled the community to weigh up the minimum costs of differing levels of reliability against the benefits in terms of increased levels of service.

6.4.5 Discussion

As elaborated in the conceptual framework, the performance of a system subject to fluctuation and disturbance is much more than a combination of the performances of the individual components, and failing to consider the interactions between the components leads to two critical limitations. Firstly, the performance of the system is likely to be systematically overestimated leading to a false sense of confidence. Secondly, opportunities to improve the performance of the portfolio through diversification are ignored or systematically underestimated, forcing the planner to rely on redundant capacity alone, which, based on the findings of the conceptual framework, is typically a more expensive and less robust response.

The case study demonstrated how the concepts of resistance may be applied as practical design templates. The mechanism of functional diversity highlighted how a diversity of sources, and resources with differing spatial and temporal sensitivities can improve performance subject to variability and fluctuation, while the mechanism of structural

[29] Note that the remaining portfolios approach complete reliability but have a much higher cost, so were excluded from this chart for improved clarity.

complexity drew focus to network connections between temporal and spatial scales, suggesting a novel configuration of rainwater, greywater, and stormwater harvesting.

The case study also extended the analytical approach of the previous case study in several critical respects.

Firstly, the interactions between the options and the baseline supply resource were captured in the analysis. This was achieved by simulating the performance of the existing reservoir in the same spreadsheet model as the performance of the options. This allowed any correlations in the response of options and the existing water source to be dynamically simulated.

Secondly, the interactions between the options comprising the portfolio were captured. Rather than modelling each option in isolation, significant interactions were explicitly modelled and therefore accounted in the assessment. For instance, if both rainwater harvesting and efficiency measures were activated, the yield from the rainwater tank would decrease to a level consistent with the reduced end-use demand.

Thirdly, the analysis applied a probabilistic rather than a deterministic simulation approach. Instead of assessing the system against historical climate directly, the historical record was applied to produce a statistical model of climate. This statistical model was then iterated using a Monte Carlo or stochastic approach to yield probability distributions of the system's performance. This extension allowed probability distributions to be developed, both for the baseline performance of the existing system, and the performance of each of the proposed strategies.

In combination these new analytical capabilities provide an improved approach to assessing the potential limitations of a risk management approach based on redundancy alone. However, because it excludes the concepts and analyses of resilience the analysis is limited in several respects.

Firstly, the analysis is by its nature passive, in that it systematically ignores the capacity of the utility to adapt to conditions as they arise. For instance, while it may be prudent to defer specific options pending critical conditions, the analytical approach ignores such opportunities.

Secondly, by focussing on the range of probable futures, the analysis can systematically underestimate the impact of less probable but potentially impactful possibilities. For instance, while the approach can ensure the probability of restrictions is restricted to a specified threshold, the method does not effectively assess the response of the alternatives to severe droughts and the associated catastrophic implications of a regional water shortage.

These limitations are addressed in the following case study.

6.5 Case study 3: Ascendance, resistance and resilience

Case study background

Although the supply-demand strategy had provided an insightful foundation on which to base their strategy for three years, Bayton Water decided to extend their analysis amid growing concerns about the impact of climate change on the performance of the water system.

From the outset they realised they that it would be incredibly costly to anticipate all possible future climate scenarios so they decided to instead focus on building a resilient strategy that could adapt to a range of possible futures.

Although the utility had a broad sense that resilience was to do with adaptability and recovery from disruption, the precise strategies for building resilience into a water system were unclear. Furthermore, the utility didn't have much idea how to assess their performance in building resilience beyond applying a coarse subjective resilience score.

The analytical team therefore delved deeper into the concepts and analyses identified in the framework under the resilience attribute.

6.5.1 Specifying the objectives

Similar to the two approaches for incorporating resistance, the framework identified two approaches for specifying resilience objectives:

- a 'possibilistic approach' whereby the alternative strategies are tested against plausible contingencies
- a 'probabilistic approach' whereby the alternative strategies are optimised using a form of decision analysis.

The key sources of climate change uncertainty for the city included the choice of emission scenario, the assumptions applied in building the climate model, and the uncertainties associated with downscaling global climate models, each of which were difficult to express as quantitative probabilities. The analytical team therefore decided to incorporate climate change uncertainty using a suite of climate change scenarios. Two core climate change scenarios were defined, broadly corresponding to the upper and lower bounds of plausible climate change arising from the global projections. In addition a suite of 'black swan' supplementary climate scenarios were elaborated to ensure the water resource strategies could sustain water supply during severe climate change realisations.

The original probabilistic approach for modelling climate variability was maintained, resulting in a hybrid of scenario-based and probability-based methods for incorporating climate change and climate variability, respectively.

The scenarios were expressed as a sequence of state parameters of mean monthly rainfall reductions relative to historical climate, which were in turn connected to the stochastic simulation generator. Re-running the Monte Carlo simulation for the two core climate scenarios revealed the following probability distributions of unmet demand.

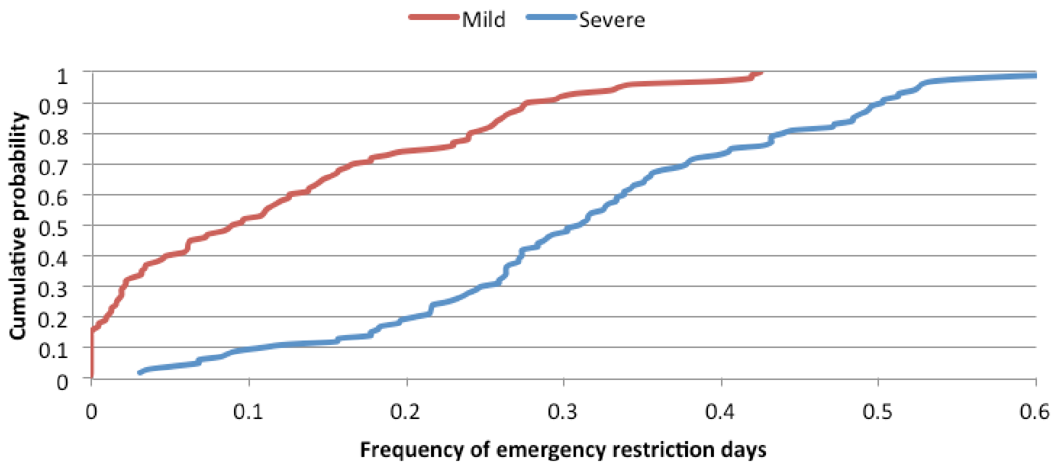

Figure 28 – Cumulative probability distribution for the frequency of emergency restriction days subject to mild and severe climate

As shown in Figure 28 above, both scenarios indicate a probability of emergency conditions well above the 0.05 threshold of acceptability, with the mean probability of emergency restriction days at 0.1 and 0.32 for the mild and severe climate change scenarios, respectively.

6.5.2 Identifying the strategies

The conceptual framework suggested two broad mechanisms for improving the performance of systems subject to shocks and shifts:

- functional flexibility, which in the urban water context implies the development of options that can more readily respond to circumstances as they arise
- structural modularity, which in the urban water context implies the development of granular, separable and combinable components.

In the context of water resource planning, the team decided that functional flexibility broadly aligned with what they had previously termed 'drought contingency planning'. That is, in addition to their long-term supply-demand strategy, they had another planning task of preparing a set of emergency measures to be used should a drought occur. However, the mechanism of functional flexibility suggested there may be benefits to integrating such drought contingencies within their long-term supply-demand strategy. That is, rather than undertaking drought contingencies as a separate exercise, they decided that those contingencies should be included in the dynamic simulation to ensure the city could withstand severe climate change scenarios effectively. Taking this step further, all large capital investments could potentially be specified using safe policy triggers, thereby minimising the probability of investing in unnecessary assets without compromising on the security of the system.

Similarly, Bayton Water already had familiarity with the mechanism of 'structural modularity' in the staged development of large capital investment programs. However, the mechanism suggested there may be benefits in taking the principle further – not just for capital deferral reasons but for maximising investment flexibility (or minimising investment 'regret'). The team therefore analysed the option portfolio to identify any opportunities to break options down into more modular components.

Consistent with the identified mechanisms, the option models were modified in two respects. Firstly, options were reconfigured to apply specific triggers where possible. For instance, the more expensive desalination options were reconfigured as 'readiness options' that would only be triggered when storage reached a critical reservoir storage threshold.

Secondly, options were broken up into separate stages or modules where possible. For instance, instead of constructing the desalination plant in a single stage, the plant was split into two modules. Although the two-stage version was more expensive overall, this approach had the value of incorporating the flexibility to build one but not both of the components.

While the resistance approach introduced the notion of 'portfolios', the resilience approach introduced the notion of 'strategies' or a suite of logical option triggers that give rise to different portfolios subject to the information available at a future point in time.

Three broad strategies were identified, which for convenience were termed 'proactive', 'reactive' and 'opportunistic'.

The 'proactive' strategy attempted to provide sufficient resistance to withstand the most severe scenario using an approach broadly consistent with the case study above but subject to the more severe climate change scenario suite. The resulting strategy therefore corresponded to the optimum portfolio assuming the utility had no ability to adapt to circumstances as they arose.

The 'reactive' strategy heavily relied on a 'wait-and-see' approach whereby options were only implemented if and when they were required. Options were scheduled using a set of triggers defined by specific storage thresholds, ordered with reducing cost-effectiveness. This had the benefit of almost entirely avoiding unnecessary investments, but by leaving investments to the latest stage possible this strategy precluded many of the more cost-effective efficiency and source substitution opportunities.

Finally an 'opportunistic' strategy was developed whereby low cost efficiency and source substitution measures were implemented pre-emptively as cost-effective opportunities arose such as new greenfield development releases. Larger capital measures such as desalination were implemented as late as possible based on the same contingency-based approach as the reactive strategy.

Consistent with the strategy-based approach, the option models and portfolio selection tools were modified to allow the adaptive triggers to be switched off (with the result that they reverted to their specified launch year) or switched on (activating them based on their specified reservoir storage threshold).

Three new portfolios were established consistent with the three identified strategies:

- The 'proactive' strategy had all options activated and the adaptive switches switched off.
- The 'reactive' strategy had all large capital options activated (i.e. centralised recycling and desalination) and the adaptive switches switched on.
- The 'opportunistic' strategy had all options activated and the adaptive switches switched on for the capital options only.

6.5.3 Assessing the strategies

As distinct from the resistance case study, all strategies met the minimum level of service owing to the way the strategies were established. That is, the adaptive triggers 'forced' the portfolio to be maintained above the emergency storage threshold by installing new plant in a shortfall situation.

In the absence of a reliability criterion, the key decision-making metric for resilience assessment was therefore the probability distribution of the net present value of the strategy subject to the suite of scenarios. The results for the three strategies are shown below.

Portfolio	Mean NPV Cost	
	Scenario 1 (Moderate)	Scenario 2 (Severe)
Proactive	$28m	$28m
Reactive	$24m	$26m
Opportunistic	$18m	$22m

The proactive strategy performed the poorest of the three. This may be attributed to the inability of the strategy to react to circumstances as they arose, often leading to large investments that were significantly beyond requirements.

The reactive strategy performed marginally better than the proactive strategy owing to the deferral of lumpy capital investments in the less severe climate realisations. However, its performance was marred by the exclusion of the more cost-effective but incremental efficiency and source substitution measures.

The opportunistic strategy performed the best of the three strategies. The reasons it performed better than the reactive strategy became clear in the modelling process. Firstly, there were a number of cost advantages that could only be exploited if taken up during the initial development of specific development areas. Secondly, the reactive strategy had to lean heavily on relatively 'lumpy' infrastructure investments that could be implemented rapidly, such as recycling and desalination. Expressed through the lens of the conceptual framework, by pushing too hard for functional flexibility the 'structural modularity' of the strategy was undermined.

> ***Epilogue***
>
> The analyses developed by Bayton Water provided the foundation for a flexible strategy capable of responding to a broad range of possible futures. Furthermore, the analyses provided a robust strategy for deferring and possibly avoiding investments in costly desalination and reservoir augmentation investments.

6.5.4 Discussion

The case study extended the analyses provided in the previous case study in several key respects.

Firstly, the case study applied a hybrid approach for incorporating uncertainty which included both scenarios and stochastic simulation. The stochastic simulation approach applied in the previous case study was maintained as a means for incorporating weather variability – that is, those daily and seasonal fluctuations around the underlying climate state. However, scenarios were applied for incorporating underlying shifts in the state of the climate. Scenarios represented the most appropriate analytical approach as the assignment of quantitative probability distribution functions to alternative climate scenarios would have been difficult and highly contentious, a situation that is not unusual when addressing shocks and shifts in conditions.

Secondly, consistent with the mechanism of functional flexibility, many of the options were expressed as a set of decision logics or policies, rather than as actions at a fixed point in time. This allows the options to respond to conditions as they evolve – reducing the probability of unnecessary investment.

Thirdly, consistent with the mechanism of structural modularity, many of the options were broken down into several incremental stages, thereby minimising the strategy's risk of under or over investment.

These three innovations allowed the analyst to develop cost-effective strategies for addressing a much wider range of possible futures.

6.6 Conclusions

The thought experiments presented above highlight how the conceptual framework proposed in this thesis leads to a different set of questions and responses for different problem situations. More specifically, the case studies highlight how different problem situations with qualitatively different drivers give focus to different attributes and therefore qualitatively different analytical approaches and responses.

Secondly, the case studies demonstrate how the heuristics may be applied to develop fit-for-context assessments.

- The first case study highlights a range of treatments for incorporating objectives into an assessment and a resulting range of analytical approaches for assessing the ecological and economic impacts.
- The second case study highlights a range of treatments for incorporating variability and fluctuations in an assessment process.
- The third case study highlights a range of treatments for incorporating shocks and shifts in an assessment process.

Thirdly, the case studies demonstrate the tensions and alignments that may arise when attempting to combine the attributes into an integrated response.

For instance, the second case study highlighted how variability and fluctuation can present a significant challenge to the core objective of providing affordable services, particularly if restricted to a strategy based on redundancy measures alone. However, by extending the planning process to incorporate the concepts and analyses of resistance, the case study demonstrated how the planner can create services that is both affordable and reliable by a nuanced application of the concepts and methods of functional diversification.

Similarly, the third case study demonstrated how an approach based solely on a resistant stance can break down when exposed to potentially large shifts in conditions. However, by applying an integrated approach that includes both resistant and resilient stances (i.e. the 'opportunistic strategy'), the case study demonstrated how those tensions might be effectively reconciled.

The case studies therefore provide a clear demonstration of the benefits of the integrated perspective and approach afforded by the conceptual framework in providing the most cost-effective means for maintaining system robustness even in severe climate change scenarios.

7 Key findings and contributions

This chapter analyses the key findings and contributions arising from the thesis with respect to the four research questions outlined in Chapter 2.

7.1 Research question 1

What attributes and mechanisms have been observed to underlie systemic performance in ecology and economics?

- **a) What are the key drivers for systemic performance?**
- **b) What characteristics are required for systemic performance?**
- **c) What mechanisms underlie the development of those attributes?**

7.1.1 Key findings

A broad set of ecological and economic concepts were analysed and synthesised in Chapter 3 to address this question. Three attributes were observed to underlie healthy ecological and economic systems: the capacity to thrive despite resource scarcity and competition (termed 'ascendance' in this thesis); the capacity to absorb variability, fluctuation and disturbance and remain essentially unchanged (termed 'resistance'); and the capacity to adapt with shocks, shifts and perturbation and avoid systemic failure (termed 'resilience').

Two mechanisms were observed to underlie each attribute: one mechanism traced the types of activities or processes or 'functional' characteristics of the system, and the other mechanism described the organisation or 'structural' characteristics of the network.

Ascendance was observed to arise from the differentiation of intensive functional activities (termed 'functional intensity') and the connection of functional components to form extensive, synergistic assemblies (termed 'structural integrity').

Resistance was observed to arise from the development of functional activities with different sensitivities to the suite of probable disturbances (termed 'functional diversity') and the assembly of functional components within complex, nested networks capable of effecting compensatory negative feedback (termed 'structural complexity').

Resilience was observed to arise from the development of contingent functional activities with different responses to the suite of possible perturbations (here termed 'functional flexibility') and the assembly of systems comprising semi-autonomous, separable and combinable functional components (termed 'structural modularity').

Perhaps the most surprising finding was the limited number of similar conceptual frameworks identified. While the conceptual review exclusively focussed on ecology and economics, the broader literature review of the thesis spans a much wider range of disciplines including ecological economics, engineering, integrated assessment and systems theory. Despite this broad scope of reviewed literature only three similar conceptual frameworks were identified. The prolific literature on specific concepts and dearth of conceptual frameworks is a clear indicator of the preference in academic discourse to focus on what Boyer (1990) calls the *scholarship of discovery* at the expense of the *scholarship of integration*.

7.1.2 Contributions

The conceptual framework is a novel contribution in and of itself, and is associated with three novel contributions with respect to the reviewed literature.

Firstly, the framework identifies the specific drivers that motivate each of the attributes and mechanisms, providing an informed basis for analysing and designing for systemic performance in a given context. For instance, in situations where variability and fluctuation are key concerns the framework suggests focussing attention on 'functional diversity' and 'structural complexity'. On the other hand if the environment is characterised by surprise shocks and shifts then 'functional flexibility' and 'structural modularity' are likely to prove more fruitful areas of focus. The framework therefore moves beyond simply recommending a list of desirable characteristics by providing a means to identify which mechanisms are likely to be most instrumental for a given situation.

Secondly, the synthesis reveals a novel set of 'functional-structural' mechanism dualities underpinning each attribute. Alfred Marshall's 'differentiation-integration' paradox in economics, the 'competition-facilitation' paradox in ecology, and George Stigler's 'adaptability' and 'divisibility' strategies all follow a consistent pattern. That is, they each represent alternative frames of reference for a similar underlying form or 'duality'. Borrowing from a distinction commonly applied in ecosystems ecology, the two elements of each pair were respectively termed 'functional' (or pertaining to the component processes) and 'structural' (or pertaining to the system assembly). A similar pattern was then observed in the mechanisms underlying resistance in the conceptual duality of 'functional diversity' and 'structural complexity' – two concepts that are still quite conflated in contemporary ecological literature. These dualities are valuable because they provide 'two sides of a coin' that are both critical for analysing, and therefore designing for, systemic performance in specific contexts.

Thirdly, the framework provides new terms and distinctions to analyse the tensions that can occur among the attributes and mechanisms. The conceptual analysis found theoretical and empirical research suggesting that the attributes and mechanisms can often be conflicting. For instance, the review found that highly resistant systems can be very strong but also very brittle in situations of surprise shocks and shifts. Similarly, the review found that the mechanism of structural modularity can often undermine the efficient linkages necessary for structural integrity. However, inversely, evidence was also presented of systems that effectively overcome the apparent ‘trade-offs’ between the attributes and mechanisms. The analysis therefore suggested a nuanced model in which tensions may be reconciled through ‘alignment’.

The conceptual analysis also contributed several methodological innovations beyond the research questions.

The most obvious is the exercise in interdisciplinary conceptual analysis. The review presented in Chapter 2 demonstrated that conceptual translations between ecology and economics are by no means new, spanning back to the formalisation of both disciplines. However, the review also indicated that much of this translation has struggled to rigorously translate concepts, metaphors and models between disciplines.

The review highlighted several examples of the challenges of interdisciplinary translation. For instance, when attempting to translate concepts it was important to pay attention to the similarities and differences between the source and destination contexts. For example, Chapter 2 found that the translation of the organismic concept of metabolism to analyse cities was associated with several issues, and that cities are much better modelled as ecological and economic systems. Similarly, the review in Chapter 3 found that the organismic metaphor of succession as originally promoted by Clements led to an inappropriately deterministic model of ecological development, giving rise to the Gleesonian view of ecological development shaped by disturbance.

However, the review also highlighted the opportunities for interdisciplinary learning. The review found that the economic and ecological literatures each had strengths and limitations that could potentially offset one another. For instance, while the economic literature had a rich analysis of the functional mechanisms overall, it had much less to contribute regarding the structural mechanisms. Inversely, the ecological literature provided a much more nuanced analysis of the structural mechanisms, particularly the mechanism of structural complexity. The review therefore highlighted several prospective opportunities for deeper interdisciplinary learning, including research into how structural complexity and modularity could manifest in economic systems and how economic notions of functional diversity and flexibility could potentially inform ecological models.

The approach developed in this thesis therefore provides a rare attempt at using the time and rigour afforded by doctoral research to build interdisciplinary learning and consequently, this thesis provides a case study of its challenges and opportunities of interdisciplinary research.

The second key methodological innovation was the historical approach applied in the conceptual analysis. The initial review found that contemporary literature suffered from two critical limitations. Firstly, the contemporary literature is inherently *biased* in its focus on concepts that are relatively new. Secondly, perhaps owing to the increasing practice of quantitatively assessing publication rates in the academic community, the contemporary literature was observed to suffer from a *low 'signal to noise ratio'*, with a relatively small proportion of publications contributing genuinely novel conceptual insight.

The conceptual analysis therefore adopted a historical approach. This involved firstly identifying the conceptual clusters in the contemporary literature and then identifying the most cited literature. This process was repeated back in time to identify the 'thick branches' of conceptual refinement through time. This process was then reversed to trace their development forward. In doing so the synthesis was able to develop a clearer picture of the conceptual development through time.

The exercise provided a unique perspective on both ecological and economic discourses. Firstly, it provided a less biased perspective of the concepts of systemic performance with due regard to the historical literature. For instance, while performance under conditions of scarcity and competition doesn't feature prominently in contemporary resilience literature, the historical literature provided a rich analysis of the subject. In turn the historical approach brought to focus its more modern descendant, 'ascendancy' theory – a field of inquiry that the analysis suggests deserves greater attention. Secondly, the historical perspective revealed that conceptual development is not consistently progressive, with many insightful contributions forgotten, only to re-emerge several decades later.

7.2 Research question 2

How do the concepts of systemic performance meaningfully translate to the planning and design of urban water and energy systems?

a) How do the concepts differ from those applied in energy and water planning?

b) What significant new insights do they offer?

c) How could those insights translate to tangible changes in the design of energy and water systems?

7.2.1 Key findings

An extensive translation and analysis of the conceptual framework was undertaken in Chapter 4.

Ascendance theory was shown to provide a coherent conceptual framework for integrating the physical and economic performance of urban water and energy systems. Specifically, the conceptual framework situates urban water and energy systems as components of their supporting economic and ecological systems. In so doing the framework is shown to provide the conceptual grounding for a suite of emerging best practice planning approaches, including multi-scale economic assessments and integrated environmental objectives.

With respect to the mechanisms of ascendance theory, the mechanism of functional intensity was shown to provide a conceptual grounding for emerging best practices including end-use efficiency, source substitution, and recycling, while the mechanism of structural integrity was shown to provide the conceptual basis for assessing the strengths, limitations and appropriate roles of distributed water and energy systems.

Resistance theory was shown to provide a platform for a more systemic response to variability and fluctuation. A series of opportunities was revealed by shifting attention away from the reliability of individual components toward focussing on the performance of the system as a whole. These opportunities included a more accurate picture of systemic risk, and a more comprehensive and potentially more cost-effective range of risk management responses.

With respect to the mechanisms of resistance theory, the mechanism of functional diversity was shown to provide a set of grounded strategies for diversifying energy and water resource portfolios, while the mechanism of structural complexity was shown to suggest a set of novel system configurations for improving systemic reliability, including building bi-directional compensatory feedback across system scales and focussing on 'accessibility' to supply, rather than adding network redundancy alone.

Resilience theory was shown to provide an improved stance for responding to shocks and shifts. Where conventional risk management leans heavily on prediction and a defensive stance to shocks and shifts, resilience theory was shown to offer energy and water planners an opportunity to affordably plan for and adapt to a wider range of possible futures.

With respect to the mechanisms of resilience theory, the mechanism of functional flexibility was shown to align well with existing strategies applied in emergency planning that could offer energy and water planners more widespread benefits if integrated with strategic planning, whereas structural modularity was shown to lend a grounded basis for assessing the opportunities and roles of more modular energy and water networks.

7.2.2 Contributions

The most obvious contribution of the translation presented here was in highlighting opportunities in contemporary energy and water systems design and planning. For instance, while 'functional diversity' is receiving increasing attention through, for instance, the new paradigm of 'portfolio-based planning', 'structural complexity' has so far received limited attention from planners and designers. Similarly, 'structural modularity' receives far less attention than 'functional flexibility' – providing a clear opportunity for further investigation.

However, the translation provides a significant contribution even where corresponding strategies already exist within contemporary best practice systems design. That is, the conceptual framework situates those design strategies according to their strengths, limitations and effective roles in building systemic performance. For instance, while diversity and flexibility are often cited in the same sentence by planners and designers, the framework suggests that promoting diversity is likely to be effective for preparing for relatively frequent and predictable disturbances, while flexibility is likely to be more effective for relatively infrequent and difficult-to-predict shocks and shifts. The translation therefore provides energy and water planners with the beginnings of a thinking tool for better integrating best practice systems design concepts in a much more nuanced manner that is fit for purpose.

7.3 Research question 3

How can systemic performance be assessed?

a) What analytical methods are available for assessing each concept?

b) **What are the strengths and limitations of each method?**

c) **In what situations is each method most useful?**

d) **How can the analytical methods be combined to form coherent analytical processes?**

e) **What are the considerations guiding the formation of these analytical processes?**

7.3.1 Key findings

A broad set of analytical methods was identified, analysed and synthesised in Chapter 5.

The review found that a range of analytical methods is already available to assess the attributes, each with inherent strengths, limitations and effective roles.

With respect to ascendance, the review analysed two classes of analytical methods for assessing ecological and economic ascendance. To assess ecological ascendance, the review identified a broad range of methods including material flow analysis, material input per unit service analysis, ecological footprint analysis, and life cycle analysis, while to assess economic ascendance the review focussed on cost-effectiveness analysis and cost-benefit analysis and their relative strengths and limitations. Furthermore, the analysis identified a range of suitable strategies for integrating ecological and economic ascendance, distinguished largely by the analyst's underlying preference for quantifying objectives either as monetary criteria or as fixed constraints.

With respect to resistance, the review analysed two broad approaches for assessing the performance of systems subject to variability and fluctuation: a 'possibilistic approach' based on scenario analysis and a 'probabilistic approach' based on a combination of uncertainty analysis and portfolio analysis. Instead of recommending a preferred option, the framework identified the strengths, limitations and effective roles of both approaches, and showed that in some situations a hybrid approach may be preferable.

Similar to the analytical methods reviewed in resistance assessment, two broad clusters of assessment methods were analysed for assessing resilience (i.e. the performance of systems subject to shocks and shifts): one was based on contingency analysis and the other was based on decision analysis and/or real options analysis. Similar to the review of resistance assessment methods, the framework pointed out the strengths of both approaches and how they may be usefully applied in combination.

The review found that the attributes can largely be assessed using existing analytical methods and proposed an approach for identifying the appropriate combinations of methods for a diverse range of problem situations.

7.3.2 Contributions

Based on a review of existing literature, the review of analytical methods presented here appears to be novel in several respects.

Firstly, the review appears to be unique in adopting an agnostic approach to several key methodological divisions. The first, most obvious division, is the so-called 'monetisation frontier'. That is, the reviewed analytical syntheses all appear to adopt a strong preference for either comprehensive monetisation through cost-benefit analysis, or purely financial analyses employing cost-effectiveness analysis – with most falling in the former camp. The second clear division in the reviewed analytical syntheses is the degree to which uncertainties may be quantified: some exclusively suggest comprehensive probabilistic modelling, and others exclusively promote scenario-based approaches. In both instances this review instead explicitly highlights these divisions and adopts an agnostic attitude – highlighting instead the strengths and limitations of both approaches and how they may be effectively combined.

Secondly, the review appears to provide a novel synthesis of methods to assess resilience. The reviewed literature provided limited guidance for assessing resilience. When the subject was covered the authors provided little guidance, exclusively recommending subjective score-based multi-criteria analysis. The synthesis, on the other hand, identified two alternative means for effectively integrating resilience within quantitative performance assessments: that is, contingency analysis and decision analysis. Although the identified analyses themselves are not novel, this appears to be the first synthesis to connect them to the important dimension of resilience and analyse their strengths, limitations and effective roles.

7.4 Research question 4

Are the analytical methods practically useful?

a) Do the proposed concepts lead to novel strategies?

b) Is the application of the analytical methods feasible in terms of analytical time and complexity?

c) **To what extent do the concepts and methods offer a material improvement in systemic performance?**

7.4.1 Key findings

The practicality and value of the thesis was tested using a suite of hypothetical case studies in Chapter 6.

The first case study tested the practicality and value of applying the framework to a relatively simple water planning situation with consideration given to ascendance assessment only. The analytical framework was applied to develop an integrated assessment of ecological and economic ascendance using a mix of analytical methods including end-use modelling, cohort component stock modelling and cost-effectiveness analysis.

The second case study tested the extension of the assessment to assess the resistance of the water system to weather variability. A novel combination of methods was developed that extended the ascendance assessment by including uncertainty analysis and portfolio analysis, demonstrating a cost-effective means for planning for climate variability.

The third case study further extended the assessment process to assess the resilience of the water system to climate change. A novel hybrid approach was developed comprising a probabilistic treatment of weather variability and a scenario-based approach for incorporating shifts in the underlying climate, demonstrating how the conceptual framework can be applied to cost-effectively plan for even severe climate change scenarios.

The case studies demonstrated the value of the conceptual and analytical frameworks in providing a structured means for describing, analysing and designing for systemic performance.

7.4.2 Contributions

The case studies yielded several innovations that are apparently unique in the academic literature.

Firstly, the case studies presented here represent a novel combination of best practice forecasting methods. Specifically, the baseline modelling applies a powerful combination of end-use modelling, cohort component modelling and water balance modelling to provide a high resolution 'bottom-up' model for exploring how water demand is likely to change over time owing to incremental changes in climate, population, economic activity, regulations and purchasing preferences.

Secondly, the case studies offer a novel and practical approach for integrating probabilistic portfolio analysis with the analytical process of integrated resource planning. Conventional integrated resource planning has been criticised for assessing each option in isolation, and therefore missing important synergies and tensions between options. In the limited set of documented portfolio analysis case studies in the literature, covariance between portfolio components is measured using either subjective or market-derived statistics. Although this approach is possible for financial portfolio analyses, such an approach is typically impractical for real water and energy planning exercises where the resources typically have no suitable historical precedent. In its place, the covariance between portfolio components was simulated dynamically by connecting irrigation demand, reservoir yield, and source substitution measures to a consistent synthetic weather series. The case study therefore demonstrated a practical approach for applying portfolio analysis to real-world energy and water planning problems.

Thirdly and critically, the case studies adopted a novel combination of scenario analysis and probabilistic uncertainty analysis for modelling the delicate interplay of variability and climate change. The reviewed guidebooks and case studies all appear to exclusively promote either scenario analysis or probabilistic uncertainty analysis. However, this case study demonstrated that the two approaches, which are often characterised as conflicting, may be usefully applied in combination in order to incorporate qualitatively different uncertainties. While a comprehensive uncertainty analysis of future climate would be ideal, climate change modelling and downscaling are still highly uncertain, making probabilistic descriptions of key climate variables highly speculative. Furthermore, the analytical complexity of a comprehensive decision analysis is still typically outside the capacity of contemporary water planners. The case study therefore demonstrates how probabilistic modelling of variability may be combined with a set of climate scenarios to provide a practical hybrid response.

8 Limitations and future research

The overriding purpose of this thesis was to develop a set of improved conceptual and analytical tools for navigating the path toward cost-effective and robust energy and water systems in a changing climate. However, several significant further steps remain for the research presented here to be practically useful to planners and designers. This concluding chapter outlines the limits of the research and highlights several prospective directions for future research.

8.1.1 Concepts

Given the scope of the reviewed academic disciplines, fields, and subjects, there is still much work to do in testing and refining the various aspects of the conceptual framework. Key concepts, including structural complexity and structural modularity, are clearly in need of further refinement, while some of the conceptual dualities are entirely novel and therefore likely to be the subject of scrutiny.

A prospective next step for the conceptual research would be to establish a series of open dialogues with experts in each of the relevant subject areas to better capture the nuances of their research. For instance, the field of ecological patch dynamics was observed to offer perhaps the most fruitful academic vanguard for exploring the nuances of structural complexity, while the fields of urban and regional economics offer perhaps the most logical economic home. A forum comprising patch dynamics ecologists and regional economists might therefore offer insights to both disciplines.

The translation of the conceptual framework to urban water and energy systems is similarly incomplete. While the review demonstrated that the identified systemic performance concepts aligned reasonably well with contemporary best practice planning, there were several mechanisms that were far less developed. For instance, the conceptual mechanism of structural complexity is apparently missing in network design practice and no analytical methods or case studies were observed for assessing its benefits. The framework suggests this may be a rewarding subject for further research.

And finally, it remains an open question whether the conceptual and analytical frameworks proposed in this thesis might offer broader insights beyond water and energy systems. The frameworks were drawn from a broad base of empirical studies in economics and ecology and as such it would be quite interesting to explore whether the frameworks offer a novel perspective on the disciplines from which the concepts were drawn. It would also be interesting to explore the range of 'ecological and economic systems' to which the framework might be relevant and insightful.

8.1.2 Analyses

The thesis has identified a prospective suite of methods for assessing the systemic performance of energy and water systems and a set of considerations for integrating them into coherent analytical processes.

Firstly, an obvious next step is to test the analytical methods in a much broader range of problem situations. For instance, while the frameworks were shown to offer novel insights in the energy planning context, it remains to be seen whether the concepts and analyses translate effectively to real-world problem situations. An obvious next step would be to establish a case study to explore whether the frameworks prove useful for dealing with the challenge of transitioning toward renewable energy systems as suggested by the conceptual translation.

Secondly, further guidance will be required for the analytical processes to be readily adopted by energy and water planners. Each of the identified analytical methods is associated with methodological challenges and pitfalls that without due care can lead to biased or deceptive conclusions. Although some of these considerations and pitfalls were identified in broad terms, the synthesis and case studies are far from being a replicable guide. More accessible guidance might be offered by a guidebook and more detailed case studies.

Thirdly, improved analytical tools will be required if the analyses proposed in this thesis are to be effectively operationalised. The analyses underlying urban water and energy planning are currently split across myriad platforms in diverse institutions, making the level of integration proposed by the analytical framework all but impossible. An integrated and accessible analytical platform would dramatically accelerate the uptake of the resource planning approaches proposed in this thesis.

At the core of this research agenda is a deep optimism. We can build water systems that mimic life's capacity for vitality and conservancy. We can build energy systems that quietly harvest and efficiently apply our abundant solar income. And we can build vibrant cities that are in harmony with the ecosystems that support them. However, if we are to rise to the challenge we will need to humbly learn from nature and design our cities to mimic life's ascendance, resistance and resilience.

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Technical appendix: simulation model description

A simulation model was constructed to demonstrate and test the concepts and analyses proposed in the thesis.

The model developed from a range of similar simulation models developed by the author during a range of research projects undertaken on behalf of a range of Australian water utilities, the Water Services Association of Australia, and the National Water Commission.

This appendix describes the model structure, components and the analytical basis of each component. For further detail about the case study itself see Chapter 6 of the thesis.

Workbook structure

The simulation model is a Microsoft Excel workbook comprising the following sheets:

- the region sheet, which contains all regionally specific information including population and dwelling hindcasts and forecasts, water, electricity and gas prices, the greenhouse gas intensity of energy, water and wastewater services etc
- the end use sheets, which model the water, energy, and wastewater loads for each simulated activity (e.g. showering, clotheswashing, industry etc)
- the reservoir sheet, which contains the details of the reservoir system including catchment areas, storage volumes etc
- the weather generator, which provides stochastic daily rainfall and evaporation data for the purposes of the Monte Carlo simulation
- the balance sheet, which brings together the various end uses, the reservoir description and the weather generator outputs to to provide a daily model of reservoir storage levels
- the option sheets, which model the physical and financial impact of each intervention including new infrastructure, efficiency programs etc
- the portfolio sheet, which controls the combination of options applied in each portfolio, and which portfolio is currently applied for the purposes of the simulation engine

End use sheets

The end use sheets model the water, energy and wastewater loads for each component of the demand forecast.

Modelled activities include

- showers
- toilets
- clotheswashers & dishwashers
- basins & sinks
- pools & spas
- lawns & gardens
- industrial
- commercial
- non-revenue water

The indoor residential end use models follow a broadly similar analytical basis. Each broadly follow the following function

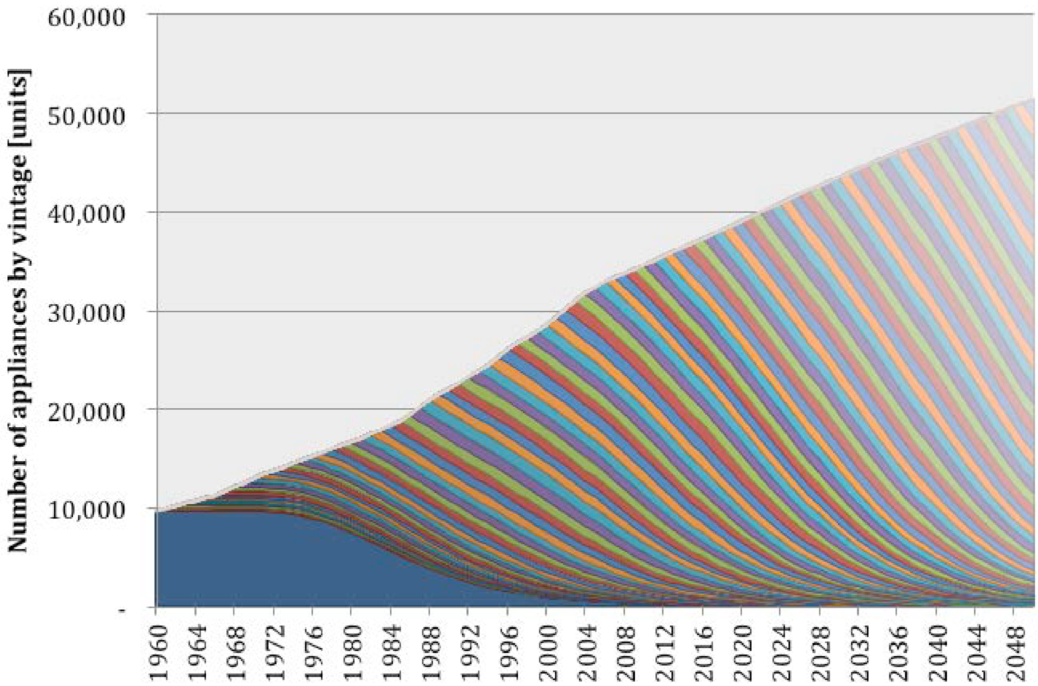
Resource consumption = behaviour x technology x stock

The 'behaviour' or the usage characteristics of each appliance, were specified using a suite of key behavioural parameters drawn from surveys and end-use measurement studies in Australia (Loh & Coghlan 2003; Roberts 2004, 2005; EES 2006; ABS 2007; ABS 2008) and validated by several end-use modelling projects in capital cities across Australia. The specified parameters were assumed to remain fixed into the future and included typical shower frequency and duration, clothes washing frequency, and dishwashing frequency.

The 'technology' or the intensity of resource consumption per unit of activity, included the volumetric water consumed / wastewater generated by different appliances, the nutrients disposed to the wastewater system, water temperatures and energy consumed per activity. These parameters were based on end-use measurement studies and sales tracking studies undertaken in Australia (EES 2006). In each example the baseline assumed that no new technologies were introduced and that the existing appliance sales shares would continue unchanged.

The ‘stock’ or the total number of each appliance was modelled using a cohort component modelling[30] approach (Muth 1973; Greene, Meddeb & Liu 1986; Riedy 2003). This involved first estimating the total number of appliances in the region based on observed appliance penetration or saturation figures and multiplying this by the number of available households. This total number of appliances was then input as the annual number of appliance sales in the first year of the model (which in this case was hindcasted to 1960), while any growth in the number of appliances was input to the model as a time series of new appliance sales.

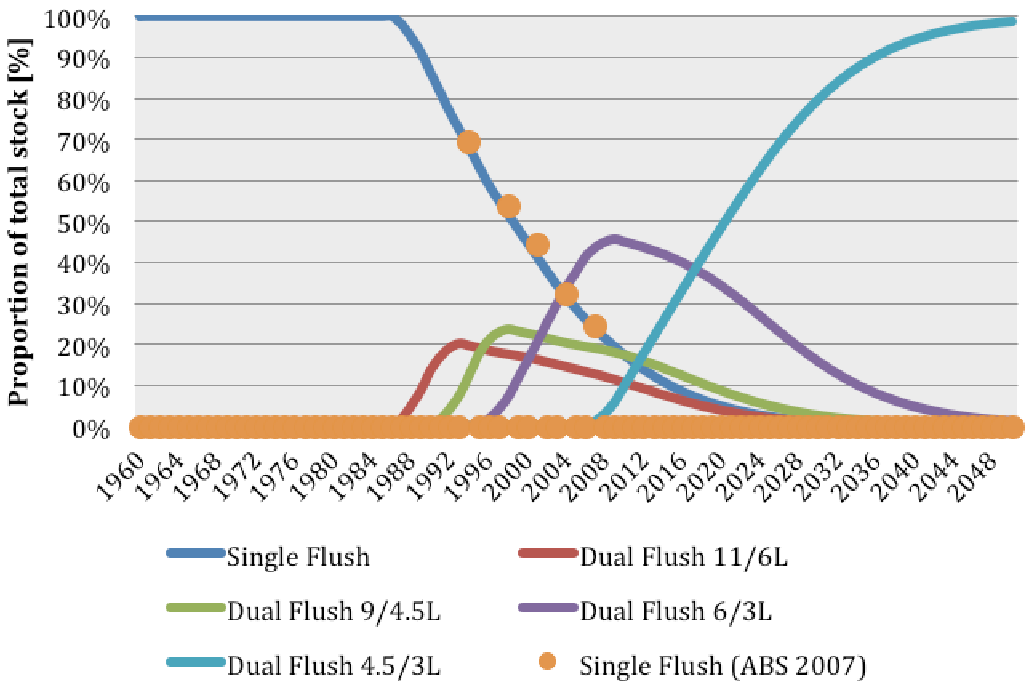
The fate of each annual ‘cohort’ of appliance sales was then modelled to determine how many of each cohort will remain in operation over time. The replacement of appliances was modelled as a lognormal decay process, with mean appliance lifetime and shape parameters determined from observed appliance replacement data where possible.



The chart above illustrates the underlying mechanics of the appliance stock models. The bands of colour represent cohorts of appliances purchased each year – that is, the annual increase in the total number of appliances plus the number of older appliances that are replaced in that year. The chart also demonstrates why the model needs to commence 50 years prior to the assessment period, as otherwise the cohort of appliances sold in the initial year (marked in blue) would be spuriously dominant in the stock mix.

30 Cohort component modelling is sometimes termed vintage stock modelling

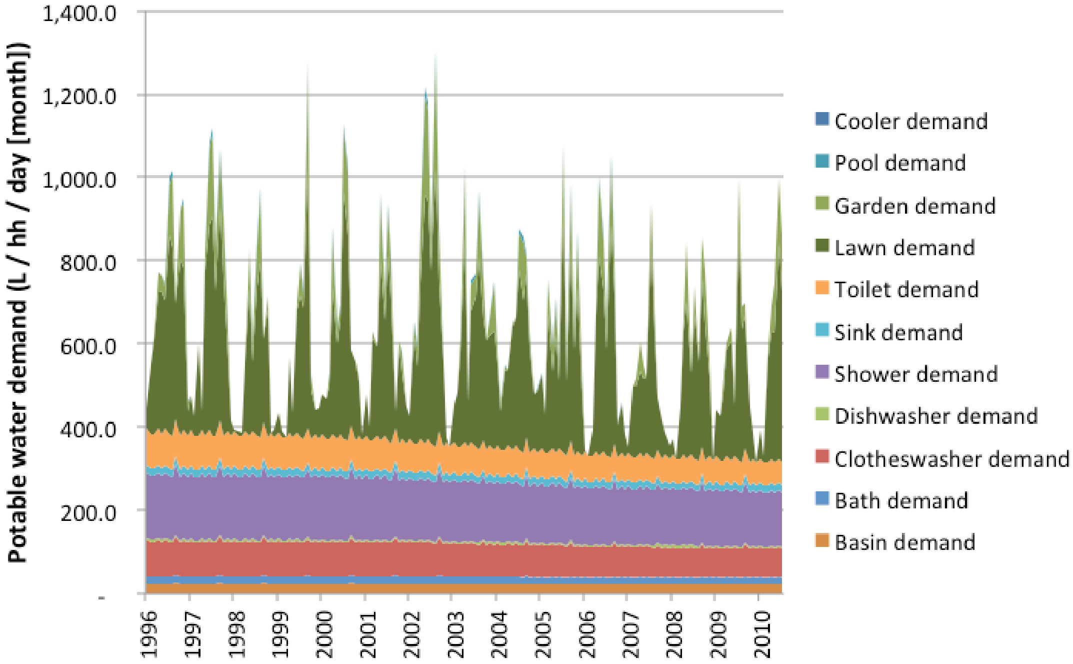
The result was an internally coherent model of the annual turnover of appliances to capture the impact of historical and future shifts in appliance purchasing preferences or regulations on the overall composition of appliance stock.



The figure above depicts the model results for the toilet appliance model developed by the author and applied in the case study. Each curve represents the growth and subsequent replacement of a new toilet technology, beginning with single flush toilets, and then showing increasingly efficient dual flush toilet models. The rate of replacement, described by a lognormal decay process, was fitted to the observed rate of replacement of single flush models following their replacement in 1984.

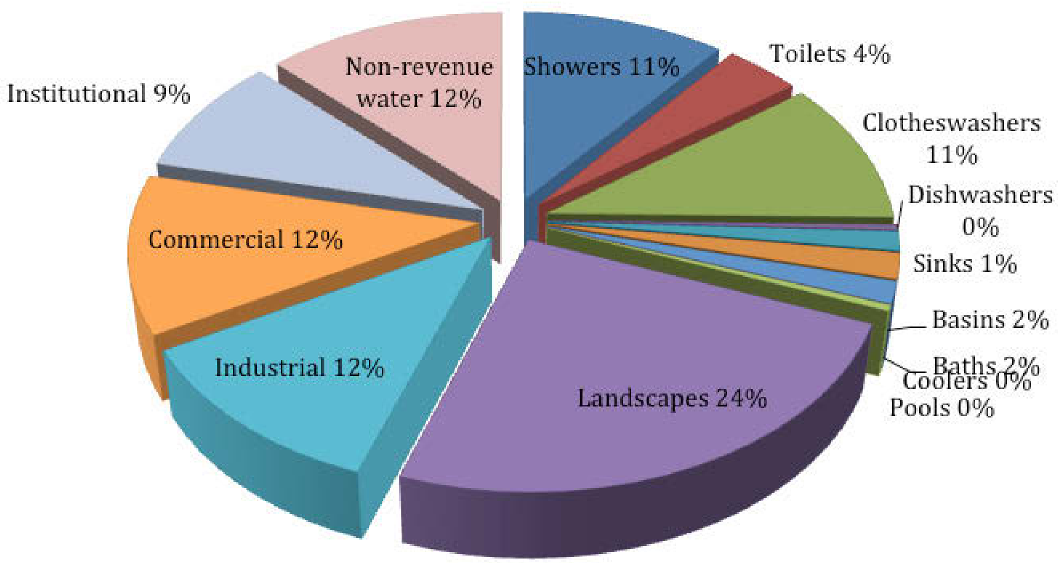
The outdoor residential end use components including lawns, gardens, and pools instead applied several water balance or 'bucket models'. That is, the pool or soil mass was modelled as a water storage of fixed capacity with rainfall as the primary input and evaporation / evapotranspiration as the primary output, and any shortage of water was made up with irrigation. This method was first demonstrated for demand forecasting purposes by the author for the City of Wagga Wagga (McKibbin, Retamal & Turner 2011), and has since been validated in consulting projects undertaken by the author in several cities across Australia.

The figure below provides the outputs of this model for a typical residential property based on historical climate data.

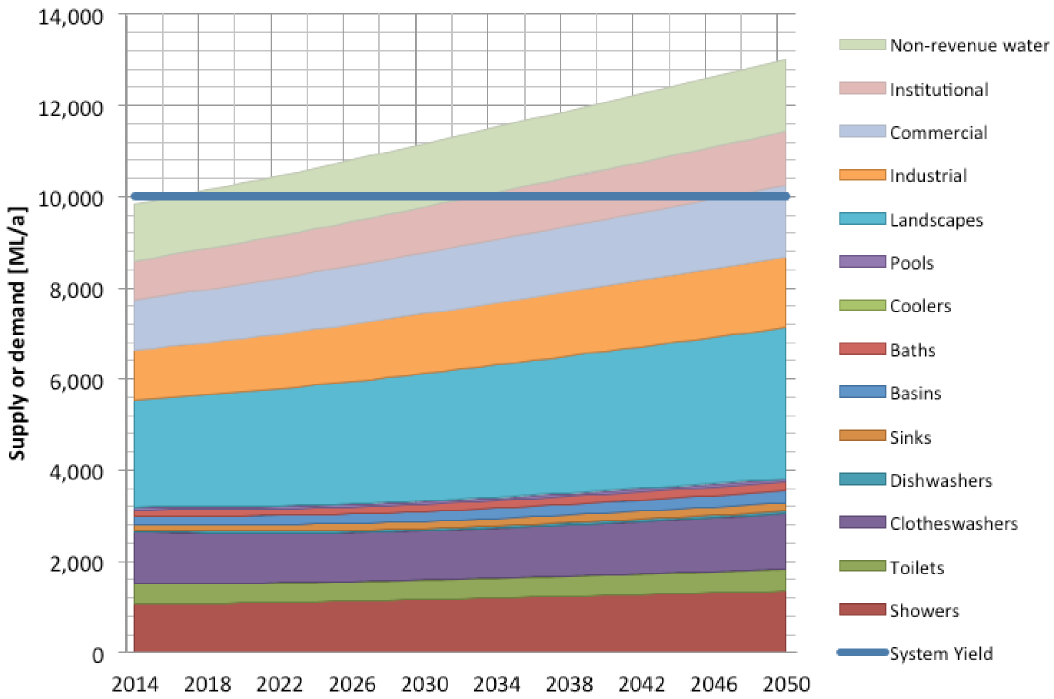


Non-residential loads were analysed using a much more simple approach owing to their relative heterogeneity and lower representation as a share of overall loads. This involved calculating a simple regression of demand as a function of population and then extrapolating that function with residential population projections.

The modelled water demand by end use in the base year is shown in the figure below.

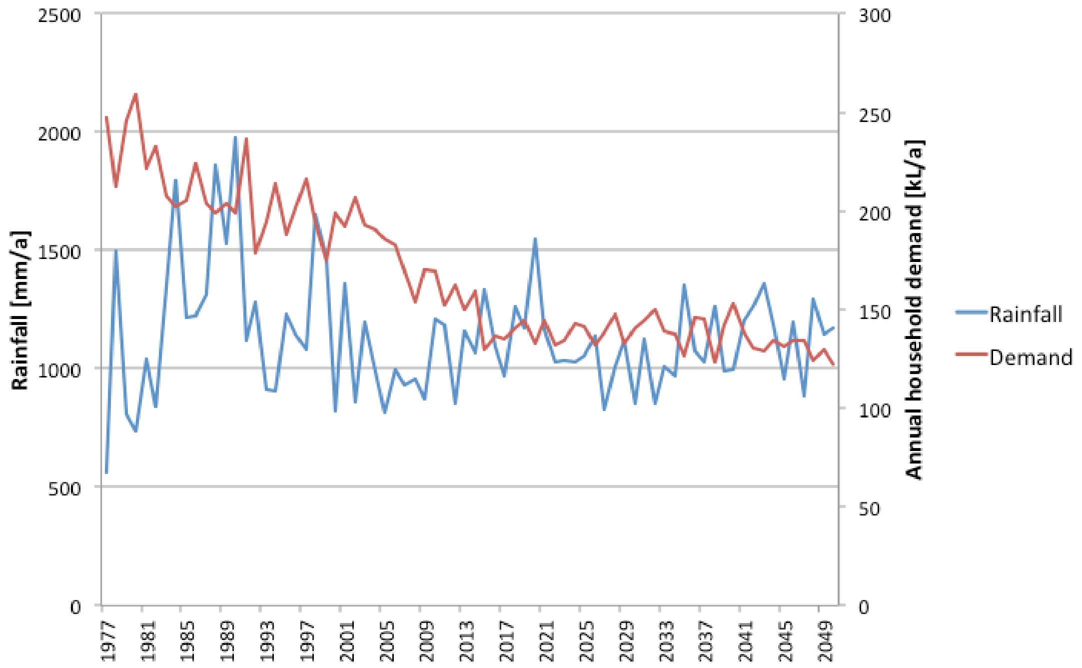


This 'current state' model is then projected into the future using projected population and household forecasts for the town. The population growth forecast was then linked to non-residential demand by assuming commercial and industrial demand would grow linearly with population, yielding the demand forecast shown below.



The weather generator

The weather generator applied an analytical approach broadly consistent with that proposed by the ClimGen team at Washington State University (Nelson 2002). This involved calibrating a stochastic Markov process to the full available record of local meteorological measurements (60 years of daily records). The weather generator was then used to generate weather sequences in a Monte Carlo-style stochastic simulation as shown below.



Note that this weather generator has several known limitations. While it adequately reflects the variance in monthly mean rainfall it fails to effectively capture inter-annually variable weather processes such as the El Nino / La Nina southern oscillation, which are significant drivers of the historical weather series shown above.

The balance sheet

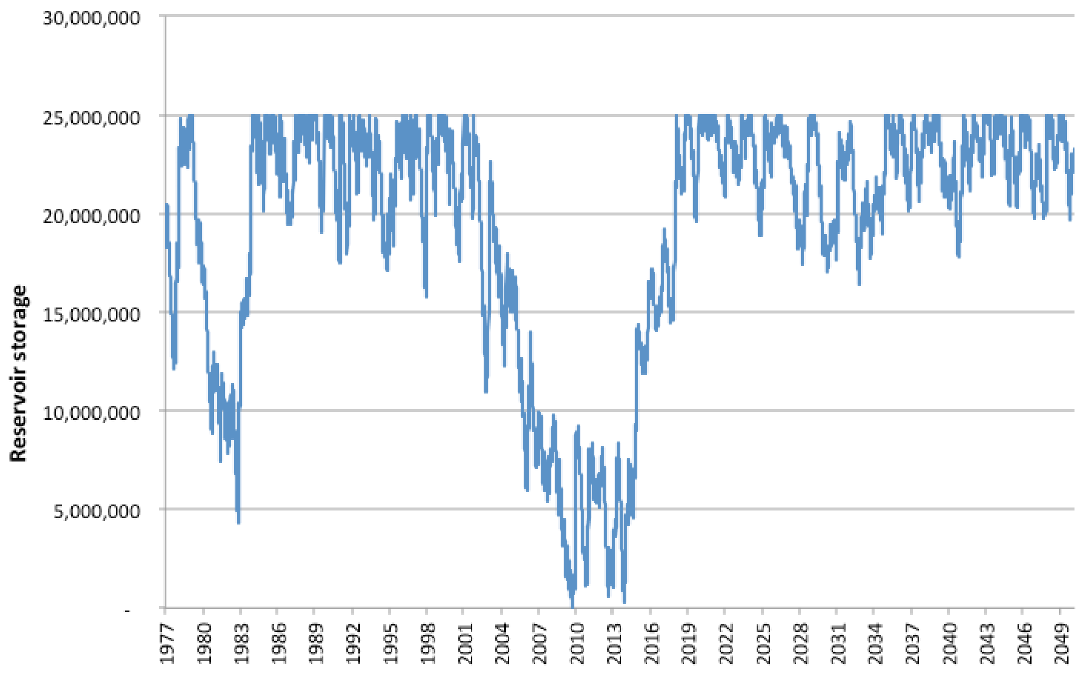
The balance sheet brings together the daily water demand forecast with the reservoir model to simulate the level of storage in the water supply system. The level of storage applied the following simple function:

Storage at end of day = Storage yesterday + daily reservoir inflows – daily reservoir losses – daily demand

Daily reservoir inflows adopted a simplified physical rainfall-runoff model with initial losses defined through a simple bucket storage model as defined above and constant continuing losses.

Note that this model has several known limitations. By only applying a single catchment node it does not replicate intra-catchment flow behaviour, which for a large catchment could be a significant driver of the inflow response. Furthermore, the model has not been calibrated to inflow observations as would normally be applied. In this instance this was a necessary compromise owing to an absence of any publically accessible models or data in the region.

The output of the model is a daily time series of total reservoir storage as shown below.



Option sheets

The option sheets model the physical and financial impacts of each of the assessed options or interventions. This includes the water consumed or saved, the energy consumed or saved, the wastewater generated or avoided, greenhouse gas emitted or avoided, and financial costs or savings borne by a wide range of stakeholders including the utility, the customer, any partner organisations, and society as a whole.

The modelled options included:

- an indoor water efficiency program
- an outdoor water efficiency program
- a decentralised greywater recycling scheme
- a rainwater harvesting rebate program
- a reservoir augmentation
- a seawater desalination plant

The efficiency and source substitution programs are broadly similar. They involve a model for the level of uptake of the program as a percentage. In this instance the assumed level of uptake was modelled as a simple flat percentage uptake of the target group (e.g. total residential dwelling stock, new dwellings etc) assumed constant over the program period.

The level of uptake for various programs were informed by historical experience implementing similar programs.

The physical impacts of the program are then modelled per participating household, with the water and energy savings based on historical evaluation studies and all other physical impacts such as wastewater and greenhouse gases derived from those savings.

The unit cost of the option is then estimated and apportioned to all relevant stakeholders. Typical costs include rebates born by the utility, water and energy bills savings for the household, program management and administration, marketing costs, evaluation costs etc.

The capital programs, including reservoir augmentation and seawater desalination broadly involve a construction phase during which no water yields are generated and then an operational phase. The specified capital costs are spread uniformly across the construction period, while operational costs are spread across the operational period and all costs are borne by the utility.

The option models were developed to account for two additional dynamics beyond those usually applied, diversity effects, and managerial flexibility effects. Diversity effects involved the positive or negative interaction effects between the options comprising the portfolio and included the impact on efficiency programs on source substitution, in addition to flow on effects of efficiency and source substitution on seawater desalination and reservoir augmentation programs. These interaction effects were built into the water balance sheets to enable their impact to be switched off for the first case study, which excluded consideration of this effect. Flexibility effects were modelled in the option spreadsheets by replacing fixed program start dates with triggers or rules. For instance, the seawater desalination and reservoir augmentation options were only activated when reservoir storages reached certain trigger levels. Similar to the interaction effects, these triggers could be deactivated, which would make the option fall back to its fixed start year. This approach enabled the diversity and flexibility effects to be removed, and allowed the case study progression described in Chapter 6 to be modelled.

The portfolio sheet

The portfolio sheet controls which of the options are activated in each portfolio, together with several other controls regarding which climate change variables are applied, whether the option sheets should include interactions with other options where specified, and whether the options should apply adaptive triggers where specified.

The portfolios are specified as a Boolean (i.e. true / false) array, with options listed in rows and portfolios listed in columns as shown in the table below.

	Portfolio 0	Portfolio 1	etc
Option A	False	True	True
Option B	False	False	True
etc	False	False	False

The portfolio sheet also has three buttons that trigger one of three VBA macros:

- Run simulation, which runs a single 50 year simulation run
- Run portfolio, which repeatedly runs the simulation as in 'run simulation' but this time a specified number of times, while recording top-level reliability and cost data for each simulation run in a table.
- Run all portfolios, which runs a full simulation sequence similar to that applied for 'run portfolio' but iterating over each of the specified portfolios, copying the simulation sequence into a new sheet.