Chapter 14
Complex, Adaptive Systems, Through Time and Across Space

Alberta Power Generation

Kevin Seel and Nigel Waters

> Given how rumours drive markets, and the way investors flock like sheep and follow the words of various gurus [traditional, market equilibrium theory] . . . is clearly unrealistic (New Scientist, Editorial, 2008, 199, #2665, p. 5).

> Dynamics and surprise are everything. Waldrop (1992, p. 271).

> "Imagine what happened to my Tatiana? She up and rejected Onegin . . . I never expected it of her!" Pushkin.

14.1 Introduction

Complexity does not mean complicated (Nijkamp 2007; Waldrop 1992, pp. 11–12). Confusion arises since complexity is a word in common use but in science it has a special meaning (O'Sullivan 2004). The first part of this chapter will consider the various definitions of complexity that have appeared in the literature. The second part will discuss a case study of the deregulation of the Alberta, Canada, electrical power generation industry, illustrating the dynamics of a complex system.

During the past few decades the geographical, social (especially economics; see the pioneering work of Arthur 1989) and natural sciences (biology, chemistry and physics) have all been subject to calls for a greater use of the methods and approaches of complexity science for, according to Richards (2002, p. 99), "complexity is one of the fastest growing and [most] pervasive branches of science". Despite flickering fires of enthusiasm for the use of these techniques over the years (Mayer 1990), these calls have not produced a consistent and sustained body of research. There is no overwhelming paradigm shift. Two recent articles, one in physical geography and one in human geography have urged a renewed interest

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A. Reggiani and P. Nijkamp (eds.), *Complexity and Spatial Networks*,
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(O'Sullivan 2004; Richards 2002) and now formal statements recommending the development of complexity in the various sub-disciplines of geography are common (for example, in land development, Doak and Karadimitriou 2007, in economic geography, Boschma and Martin 2007, and in the study of space and place, Manson and O'Sullivan 2006, among others).

This chapter will review these two commentaries in particular and provide a critique of complexity as it is being used in geography and geographic information science and allied disciplines. In the past, researchers have adopted a diversity of attitudes toward complexity science. Few were initially supportive, many were openly hostile (Brian Arthur's seminal 1989 paper was rejected by three leading journals: Waldrop 1992), and some were prescient (Hicks arguing in 1939 that it would lead to the "wreckage… of the greater part of economic theory"), while most, it will be argued here, have been far too cautious in assessing the potential of complexity analysis. Even now, it is not the majority of researchers that appreciates the rich cornucopia of rewards that awaits those scholars willing to combine the tools of complexity science with the traditional methods of their disciplinary sciences.

14.2 Part 1: Complexity Defined

Manson (2001), states that complexity has been defined in three ways: algorithmic complexity; deterministic complexity and aggregate complexity. Others, including Richards (2002, p. 99) have suggested that complexity "may be viewed simply as incorporating the continuum between 'order' and 'chaos'". Here we will follow Manson's framework in analysing how complexity science has in the past, and how it might in the future, contribute to geographic information science. In particular, we will pay attention to the problem of spatializing system dynamics.

14.2.1 Algorithmic Complexity

Although O'Sullivan (2004, p. 283) subsequently dismisses algorithmic complexity as having "no obvious application to geography", and presumably to social science in general, Manson (2001) is less hasty in his judgment noting that algorithmic complexity has two components. The first component concerns the difficulty of solving a problem couched in mathematical terms. This aspect of algorithmic complexity, Manson suggests, is less useful to geographers and yet solution complexity, frequently expressed in terms of the so-called "big O notation" (Black 2007), has been, for example, a *sine qua non* for those social scientists presenting at the triennial ISOLDE (International Symposium on Locational Decisions, http://isolde.geog.ucsb.edu/isoldeXI_about.php) Conferences ever since their inception in 1978.

ISOLDE researchers (an unusual mix of primarily geographers and operations research specialists) frequently begin their talks by stating how their new algorithm solves a problem in a fast, polynomial time when the problem was previously thought to be intractable other than by complete enumeration. Since there are vast classes of problems in transportation geography (Waters 2005) where this is important it is difficult to support O'Sullivan's dismissive view.

Manson is more positive concerning the second aspect of algorithmic theory, which relates to the simplest computational representation of a system that will reproduce its behaviour. Determination of this manifestation of the system structure is usually aided by information theory which has been more widely deployed in social science research. Manson promotes the importance of the classification of remotely sensed imagery and the impact of ecological structure on biodiversity, a topic that has seen a resurgence of interest with Costanza and Voinov's (2004) work on landscape simulation modeling (see the discussion below). Despite his support for this research, Manson ignores the work of Wilson's entropy maximizing models (1974) and its associated and extensive literature, including the ubiquitous, four-step transportation planning model that became associated with this work.

Manson (2001, p. 406) argues that a major limitation of the application of algorithmic complexity to social and environmental problems is that it "may incorrectly equate data with knowledge". This is similar to Clifford Geertz's plea for "thick description", a concept he popularized but which he acknowledged was originally developed by Ryle (Geertz 1973, p. 6). Interestingly, Ryle in explaining the language of philosophy uses cartography as a simile (see Tanney 2007). It will be shown in the case study in the second part of this chapter that providing electricity users with continuous data on the cost of the electricity consumption can help to optimize the functioning of the system, dampening the effect of the positive feedback loops within the system.

Likewise in Plato's *Phaedrus*, Socrates tells the story of how the god, Theuth, placed his invention of writing before the Egyptian king Thamus. The king argued that the new technology did not guarantee wisdom but merely "a conceit of wisdom" (Rockwell 1999; Postman 1993). From the vantage point of more than two millennia we can see now that writing did indeed provide the opportunity for endless wisdom, although few would deny that the loss of an oral tradition had its own problems and did much to disparage traditional, indigenous knowledge; Clayton and Waters 1999).

Debate over the value of data per se has reached the popular press with discussions over the value of Google's search engine and its ability to provide instantaneous access to vast repositories of data and articles. Carr (2008) asks rhetorically and provocatively whether Google is making us stupid and he too alludes to Plato's *Phaedrus*. That technology changes us is generally accepted in such modern folklore as Fubini's "Law" (Herremans et al. 2007) but in an era where data mining tools and software are widely used throughout industry and indeed academia (Miller and Han 2008; Miller 2007) it is surprising to see Manson ignoring this treasure trove of applications of the tools of complexity and related forms of analysis.

Again the popular press appears to be rushing in enthusiastically where academic angels fear to tread. Wired Magazine (2008, p. 7) introduced a series of short articles on data mining of massive petabyte data sets with this comment: “Solving scientific problems used to require grand theories. Now it just requires number crunching. Welcome to the Petabyte Age”. Examples that are provided include the Europe Media Monitor (EMM 2008). This website tracks news in 35 languages worldwide. A graph is provided that shows the top ten stories over the previous four hours. The EMM website may itself become part of the news system since news organizations may visit the site to know the stories they should reference, thus setting up a positive feedback loop. Indeed this is exactly what occurred when, in September, 2008, a Google news bot crawled on to the Sun Sentinel’s website and picked up a 6-year-old story from December 10, 2002, stating that United Airlines was seeking bankruptcy protection. The article was accessed by Income Security Advisors and distributed to a Bloomberg stock market information site. Since the story was assumed to be current United’s stock fell 75% from $12 to $3 before rebounding when the truth became known.[1]

Consequently, we disagree with Manson (2001) and argue that data is indeed knowledge, it is just a different kind of knowledge. This aspect of complexity is already extensively exploited and will have increasing importance in the coming years. Excellent examples are provided in the Handbook of Geographic Information Science (Fotheringham and Wilson 2007) by Skupin and Fabrikant (2007) and by Gahegan (2007). Their chapters on Spatialization and multivariate geovisualization show how data mining techniques can reveal patterns in the data with no understanding of the intrinsic characteristics of the variables (Waters 2009). Fubini’s so called “Law”, mentioned above, argues that people initially use new technologies to do the same things as before only faster. Eventually they come to use the technology to do new things and these new things change the way society functions and indeed change society itself: hence first we change technology and then technology changes us (Herremans et al. 2007).

In the case study discussed in Part 2 of the chapter we show how data relating to the real time cost of electricity can be used by consumers to curb peak demand and dampen the boom-and-bust cycles in the construction of generating capacity.

14.2.2 Deterministic Complexity

For Manson (2001) deterministic complexity has four primary characteristics: (1) the use of deterministic mathematics and mathematical attractors; (2) feedback processes, both positive and negative; (3) sensitivity to initial conditions; and (4) chaos. It is deterministic complexity that would appear to hold most promise

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[1] See http://www.alootechie.com/content/google-chicago-tribune-blame-each-other-collapse-united-airlines-stock-price.

for the social sciences and is the basis of our case study of the Alberta electrical power generation industry.

With respect to the first of these characteristics, May (1976, p. 460) provided a seminal treatment describing simple mathematical models of, for example, population growth (14.1):

$$X_{t+1} = \alpha X_t (1 - X_t), \tag{14.1}$$

where X_t is the current population and X_{t+1} is the future population that is dependent on X_t $(0 < X < 1)$ and on α, a growth rate parameter in the range: $0 < \alpha < 4$. When α lies in the range 1–3, the population of such a system exhibits equifinality in that it will settle on a given value equivalent to (1–1/α regardless of the initial population value at time t (Manson 2001). This final steady state value is known as an attractor. The population will die out if α is less than 1 and grow without check if α is larger than 4.

Despite the importance of these findings they are not included in the earliest texts on modelling in geography and related sciences (for example, Thomas and Huggett 1980; Burghes and Borrie 1981). Indeed their importance was not realized by the broader academic community until the 1980s. Bennett and Chorley (1978, pp. 395–397) are among the pioneers who did include an extensive discussion of the application of these models in physical–ecological systems.

The second aspect of deterministic flexibility includes feedback processes. Where there are negative feedback processes the system will exhibit stable behaviour such as that shown by an attractor. Positive feedback produces a situation where a population may grow until the system collapses or where the population declines at an exponential rate until it ceases to exist. Equation (14.1) describes a simple system and additional variables can both make the system more complex and introduce additional loops that exhibit complexity in their behaviour making prediction of the system's state increasingly difficult. Ford (1999a) describes a variety of real world systems that are suitable for modelling using a system dynamics approach and this is the approach used in our case study below.

When α is a little over 3.8 the system becomes completely random and chaotic and has no discernible attractor (Manson 2001; May 1976, p. 462). Since a deterministic equation describes the system behaviour it is not truly chaotic but is described as deterministically chaotic. Other values of α greater than 3 and less than 4 allow the system to oscillate between various attractors and become highly sensitive to small changes in the initial value of α.

This third characteristic of deterministic complexity has been described in Wilson's work (Wilson 1981) on catastrophe theory and the study of rapid jumps in the system behaviour known as bifurcations. Despite the promise of this research in the early 1980s it did not spawn the expected paradigm shift and few researchers exploited the field, though Wolfram (2002) is a notable exception. Even the study of dynamic systems along with their structure and feedback processes while hugely popular at the time of the publication of the Club of Rome Report by Meadows et al. (1972) resulted in waves of criticism (Cole et al. 1973; Vargish 1980).

Once you have "cried wolf" it is difficult to regain trust and once the direst predictions of the original limits to growth study had proven unlikely to be realized it appeared hard for Meadows et al. (1992) to gain support for the more modest prognostications that were produced by their World3 models. These outcomes included the suggestion that human use of resources and production of pollutants had by the early 1990s reached unsustainable levels; that in a world where it was "business as usual" there would be an uncontrollable per capita decline in energy use, and food and industrial production; and that to prevent this there would have to be a reduction in population growth and material consumption together with an increased efficiency in the factors of production, both energy and materials. Meadows et al.'s 1992 book, *Beyond the Limits*, sounded a note of optimism, declaring that a sustainable future was possible but that it would take a revolution in our social systems and systems of productions, a revolution that would need to be as profound as the agricultural and industrial revolutions that went before. Moreover, it would require a revolution that was as rapid as prior revolutions were gradual.

What *Limits to Growth* and *Beyond Limits to Growth* provide is, in the words of Geoffrion (1976), insight and not numbers. This is a view echoed by Nijkamp and Reggiani (1995, p. 185) when they note the importance of the logical structure of the system dynamics models used by Meadows and her colleagues. In the years since the second of these volumes was published, there has been little cause for optimism and even the simplest and most straightforward of Meadows' findings have gone unheeded as population growth continues its unchecked rise.

In the same paper, Nijkamp and Reggiani describe the mechanics of the bifurcation process and review the literature on catastrophe theory but despite noting the initial popularity of this theory and despite citing an extensive literature they too indicate that applications of the methodology were difficult (Nijkamp and Reggiani 1995, pp. 185–186):

> A weak element in catastrophe models is that the identification, explanation and estimation of critical turning points is extremely difficult since their occurrence is too irregular to be captured with sufficient statistical evidence by normal time series. As a consequence catastrophe theory has often been used for illustrative expositions rather than for predictive purposes…

To some extent recent work with system dynamics models has made the study of rapid change in system outputs and behaviour easier to study (Ford 1999a; and see the discussion of the Alberta electrical power generation industry below) but realistic models that capture the structural properties of real world systems are time consuming to build.

Chaos and fractals, the fourth characteristic of deterministic complexity, have received widespread attention in the geographical literature. Perhaps the best explanation of the usefulness of these tools, at least in physical and environmental geography, is given by Phillips (1999, p. 19) who notes that "deterministically chaotic systems are sensitive to minor variation in initial conditions and to small perturbations, such that miniscule changes or variations grow over time". To say the least, this is disconcerting since minor errors and lack of precision in input parameters can produce drastically different output as recounted by Edward Lorenz (1963, 2002) and his description of the so-called "butterfly effect" and as explained in most descriptions of chaos theory (Richards 2002).

In urban geography the most exhaustive treatments have come from Batty and Longley (1994) who have shown that the boundaries of cities exhibit self-similarity across all scales. A recent discussion by Batty incorporates a more explicit treatment of the concepts of complexity as they relate to cities (Batty 2005). The property of scale invariance has been exploited in the recent analysis of networks of all types and especially for analysing the structure of the internet (Schintler et al. 2005; Waters 2006).

14.2.3 Aggregate Complexity

Aggregate complexity relates to the interactions among components of a system. For O'Sullivan this is the most beguiling of Manson's definitions of complexity. It might be argued that the greater the interaction between entities in a system the greater the likelihood of system homogeneity. New modelling methodologies such as geographically weighted regressions are only necessary when the relationships between dependent and independent variables vary across space (Waters et al. 2007) and this is less likely to occur in a well integrated system. Across small well, integrated neighbourhoods variables that explain voting behaviour in the Canadian 2006 Federal Elections have been shown to be similar (Mawa 2009) but over larger regions and across the country powerful explanatory models may show considerable differences (Li 2009) making simple, global solutions unacceptable.

14.3 Part 2: Complexity Applied

14.3.1 Modelling Complexity through Time and Across Space: A Case Study of the Deregulated Alberta Electrical Power Generation Industry

14.3.1.1 Modelling Approaches: Privileging Space or Privileging Time

Costanza and Sklar (1985, p. 47) observe that complexity can be modelled and articulated in three ways: "Dynamic models are those articulated in time: spatial models are articulated in space; and compartment models are articulated in the system components (state variables)". Even today most models are articulated (realized and constructed) primarily in one of these three ways but most commonly either across space or through time. Susan Crow in a paper presented to the Fourth GIS and Environmental Modeling Conference held in Banff in 2000 (Crow 2000) describes the mechanics of these two primary methods of modelling complexity.

The first of these approaches, that which privileges space, can be implemented using ESRI's Model Builder (http://www.esri.com). The spatial modelling is explicit within the GIS framework but time is handled through the "stacks of maps" approach. The second method where time is paramount can be modeled using Costanza and Voinov's (2004) spatial modeling environment (SME). Here a system dynamics model is implemented for a given spatial unit and the model is then duplicated across a set of spatial cells. This is the approach used in the present study where three regional cells are modelled separately and then linked together.

We will now describe a similar approach to the modelling of the Alberta, Canada, electrical power generation industry. The model uses system dynamics together with an explicit spatial component to provide insights into how the deregulated electrical power generation market will evolve over the long term. Hirsh (1999) provided an early discussion that deregulation in the US electrical utility system might not be the panacea that eagonomics would have postulated. Indeed it might be argued that in moving to deregulated power markets Alberta paid little heed to the difficulties encountered in the UK and California (Watts 2001) and other jurisdictions and also ignored the lessons learned in the real estate, construction, mining, oil and gas and airline industries among others.

Building on the work of Baumol and Benhabib (1989), Berry (1991) has suggested that economies may be chaotic systems that can be described by deterministic, first order, nonlinear difference equations that produce extremely complex behaviours over time. Baumol and Benhabib (1989) state that there are various reasons for studying chaos including the importance of studying uncertainty in that small changes in system variables can have dramatic impacts on system behaviour (the butterfly effect) and the characterization of the full range of possible system behaviours including dramatic oscillations, the so-called boom-and-bust cycles. In addition, models that exhibit chaotic behaviour, as with all dynamic models, can be used to disprove universally held propositions such as "the allegation that profitable speculation is always and necessarily stabilizing.... Similarly, it was shown that slight lags in response can undermine apparently rational countercyclical policy" (Baumol and Benhabib 1989, p. 80). Our case study below supports both of these conclusions. Berry uses moving average techniques and Baumol and Benhabib's methodology for identifying chaotic behaviour to support his analysis of long-wave rhythms in the US economy. Writing in 1991 his best prediction was that the labour market would "bottom out" in 1995 with the next growth cycle beginning "in the first decade of the twenty-first century" (Berry 1991, p. 191). With hindsight we know that the global melt down was delayed by a little more than a decade, perhaps partially justifying King's criticism of Berry's book (King 1993). Nevertheless Berry's thesis that a dramatic collapse would occur has proven correct. That it has been exacerbated by investor "herd behaviour" or flocking (Waldrop 1992) and a lack of regulation of, for example, the derivatives market[2] provides support for the modelling approach used below and some of our conclusions.

It might have been suspected that decisions that were made by private market agents would be taken with their own selfish interests and profit maximization in mind rather than deferring to the interests of the public. What was perhaps less obvious is that these decisions were often neither rational nor well informed and reflected short term behaviour. Market participants have been influenced by perception, "herd" mentality and other psychological factors. The decisions of those involved in the power supply industry and the construction of electrical power generation plants often interact through complex, highly dynamic and counter-intuitive patterns of feedback that involve all of the other players in the system. One difficulty that the industry faced was the long lead times that power construction requires. Once a need is determined, once the demand is apparent for increased power generation and a decision is made to build a new power plant, that plant must be designed, the site must be selected, environmental regulations must be satisfied and the construction and commissioning of the plant have to occur, all before the power becomes available to the consumer. Consequently the time between the signal to act, the decision to act and the action being completed may be in the order of several years.

Other factors have confounded the supply of deregulated electrical power. These include the unusual properties of the "commodity" of electricity which is created and destroyed on demand, for the most part cannot be stored and is subject to complex processes of economics, engineering and physics, all of which interact in unpredictable ways. In modelling the behaviour of the deregulated system in Alberta a number of research questions were addressed. First, if the market functioned as intended why did investors not bring capacity into service to benefit from the extremely high power prices that existed in the year 2000 and later? Second, could investors be expected to bring online new power plants in a steady and timely fashion to keep pace with growth in Alberta's demand? Third, would power plant construction, by contrast, appear in a series of waves of boom and bust similar to other deregulated industries? The null hypothesis would be that the market would function as desired with stable prices (Fig. 14.1) while the alternative hypothesis would see "boom and bust" cycles appear in the amount paid for electricity (Fig. 14.2).

14.3.1.2 A System Dynamics Simulation Model of the Deregulated Alberta Electrical Market

To build a realistic model of the deregulated Alberta electrical power generation market a system dynamics model was developed. This is the approach that was used

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[2] See http://www.washingtonpost.com/wp-dyn/content/story/2008/10/14/ST2008101403344.html, the Washington Post article.

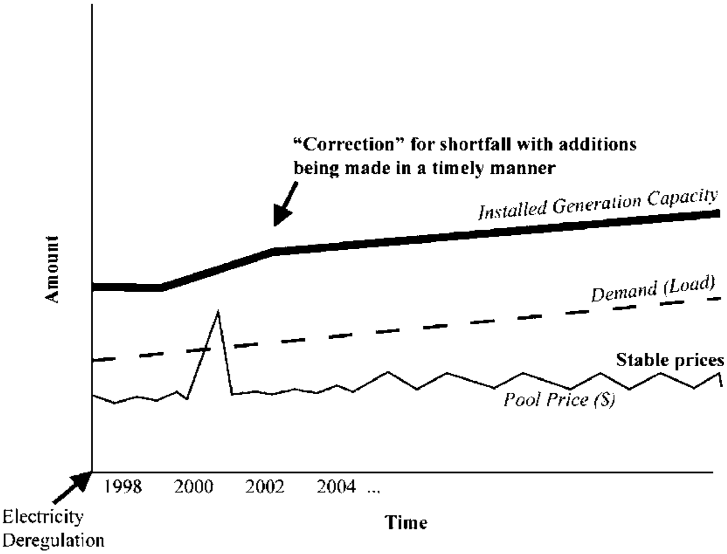

Fig. 14.1 Alberta market functions as desired

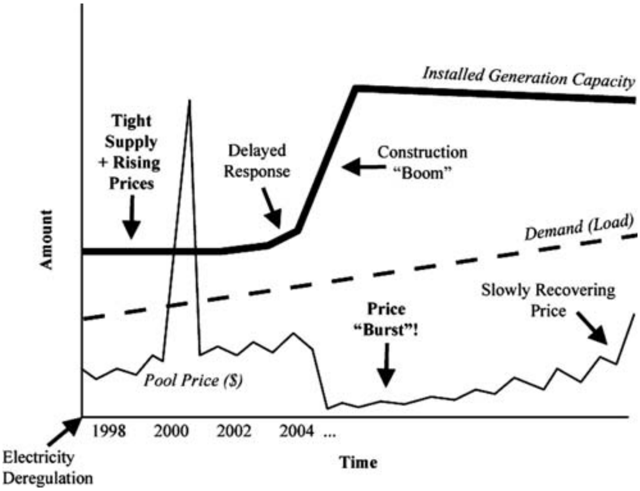

Fig. 14.2 The Alberta market functioning with "boom and bust" cycles

in *The Limits to Growth* studies and derives from the work of Forrester (1971). The assumptions are that the system behaviour is determined by system structure and that this structure is comprised of interconnected two-way feedback loops. Creating a realistic model required: a detailed representation of the actual physical system that incorporated the key feedback dynamics between modelled elements; depiction of the various forms of investor behaviour and a method for testing strategies to minimize the effect of the anticipated boom and bust cycles. Following Geoffrion (1976) we were seeking insight not numbers. The model captures the supply side, wholesale markets and transmission components of the Alberta electrical power generation system as described in the Alberta Advisory Council on Electricity (AACE) Report (2002). The model was given the acronym APPCON (Alberta Power Plant CONstruction model) contains 4,000 lines of code and is programmed using the iThink software from High Performance Systems (1990). For complete details see Seel (2004).

The APPCON model incorporates the primary components of the spatial structure of the Alberta electrical power generation system including three regional models (for north eastern, central and southern Alberta with two transmission corridors between the first and second and the second and third of these regions) and interprovincial transfers, both east and west. Generation types modelled include coal, gas turbines, cogeneration, wind and hydro although there is no representation of any large hydro plant. Figure 14.3 shows the primary elements of the modular design of the model while Fig. 14.4 shows how the model is spatialized between the three regions. Figure 14.5 provides an overview of the core model dynamics showing the key feedback processes as causal loop diagrams.

Figure 14.6 shows all the primary feedback loops within the structure of the APPCON model. Two of these loops are "reinforcing", positive feedback loops while the remaining three are "balancing", negative feedback loops. The positive feedback loops are those that model Arthur's (1989, 1996) phenomenon of increasing returns. The behaviour of the model is both moderated and "complexified" by the influence of the two negative feedback loops. As Waldrop (1992, p. 36) has noted, when discussing Arthur's work: "that's why you get patterns in any system: a rich mixture of positive and negative feedbacks...it's the mix of these two forces that produces the complex pattern...". In the figures below the "+" signs indicate positive feedback and the "−" sign a negative feedback relationship between the variables. The double hatch marks on the connector arrows indicate a time delay, an important factor in reproducing suboptimal responses of the investors in the model.

Figure 14.6, illustrating the R1 positive feedback loop, shows how new generating capacity is added to the power generation system in response to increases in demand. As demand for electricity in one of the three regions increases, the Alberta Power Pool dispatches additional capacity thus lowering the capacity reserve margin. When the annual capacity margin drops to 15% of total installed capacity this is considered to be the signal for new investment in capacity to be introduced (CERI 2002). This does not immediately translate into new construction as new plants must be designed, financed and approved by the investors. The delay may be from one to several years as the new plant must be proposed, sited, permitted,

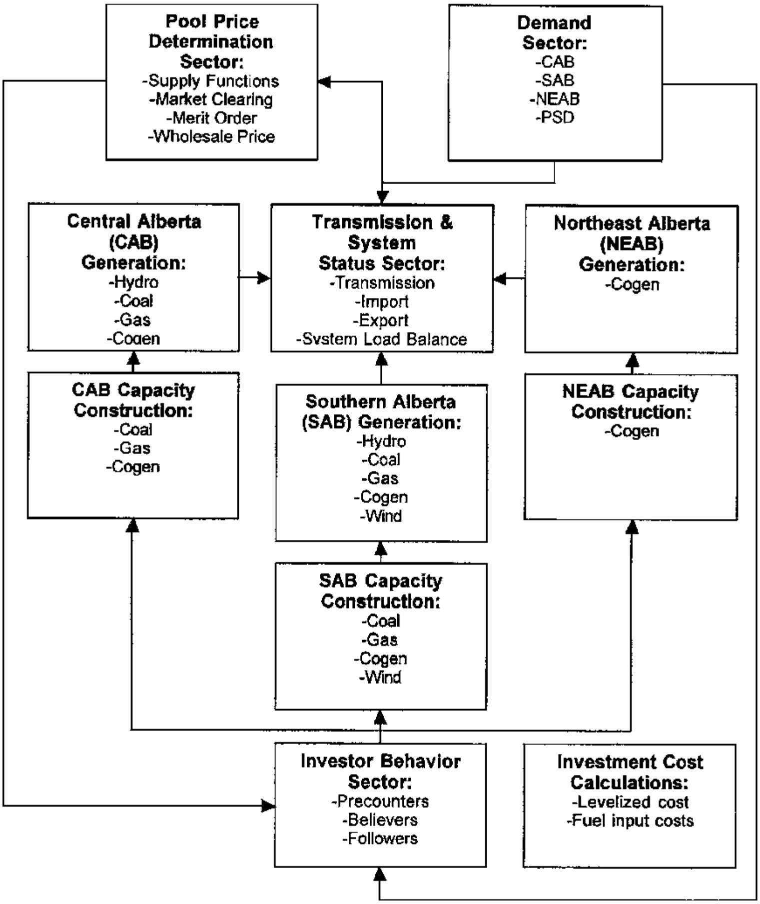

Fig. 14.3 High level structure showing modular design of the APPCON model

constructed and commissioned before it is made operational and the new capacity becomes available to the consumer.

Linked to the R1 loop and shown in Fig. 14.6 is the reinforcing, positive feedback that describes how new generation additions are a function of potential profitability. Dispatched generation is organized in a "merit order" from least to most expensive. As demand continues to rise the dispatched power becomes increasingly expensive making investment in new generation capacity increasingly attractive. Since there is a lag of one to several years between the "signal" for increased capacity and the arrival of that capacity to the consumer the use of increasingly expensive generating capacity will continue making investment appear more and more desirable. The negative feedback loops are also shown in Fig. 14.6. The first, the B1 loop, models the introduction of new generating capacity

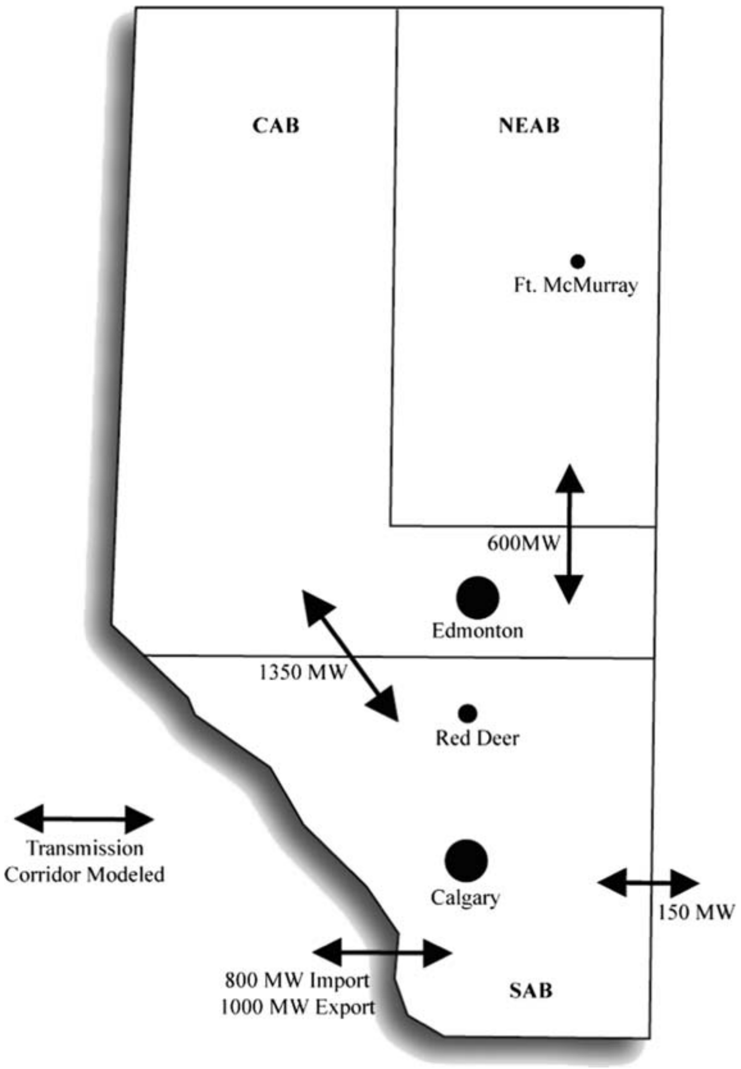

Fig. 14.4 Alberta regions and transmission corridors modeled in APPCON

and will add to the reserve margin reducing the attraction of investing it yet more capacity.

The second balancing loop, B2, illustrates investor behaviour. As new generation is proposed and enters construction, it will have an influence on the propensity of investors to enter the market. The amount off influence depends on the level of "conservatism" of the investor. Three levels of conservatism are modelled, precounters, followers and believers, listed in order from most to least conservative.

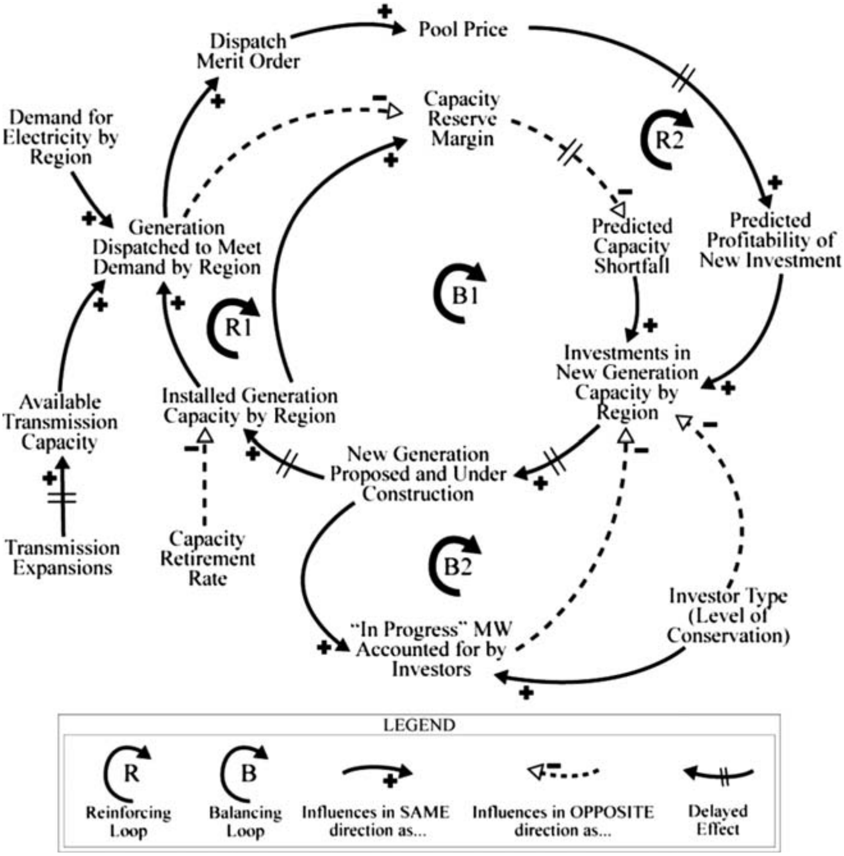

Fig. 14.5 Causal loop diagram: primary feedback loops in the APPCON model

More is said about investor behaviour below. The model, as constructed to this point, has the potential to generate undesirable "boom-and-bust" price cycles. As demand for power rises with industry expansion and population growth, price will also rise, creating the price boom. This triggers new power plant construction that, due to construction lags, may lead to subsequent over expansion of the power supply as investors react to the opportunities provided by price spikes and hence the potential for the boom-and-bust cycles to appear. Two policy mitigation strategies were embedded in the model. The first part of this loop tests the effects of a real-time, conservation response by consumers to price spikes that occur during times of peak load. In this loop consumers respond to price spikes by curtailing demand, essentially by delaying appliance use and thus reducing peak demand and preventing the capacity reserve margin dipping below the critical 15% level. Although CERI (2002) has suggested that consumers already exhibit some of this behaviour,

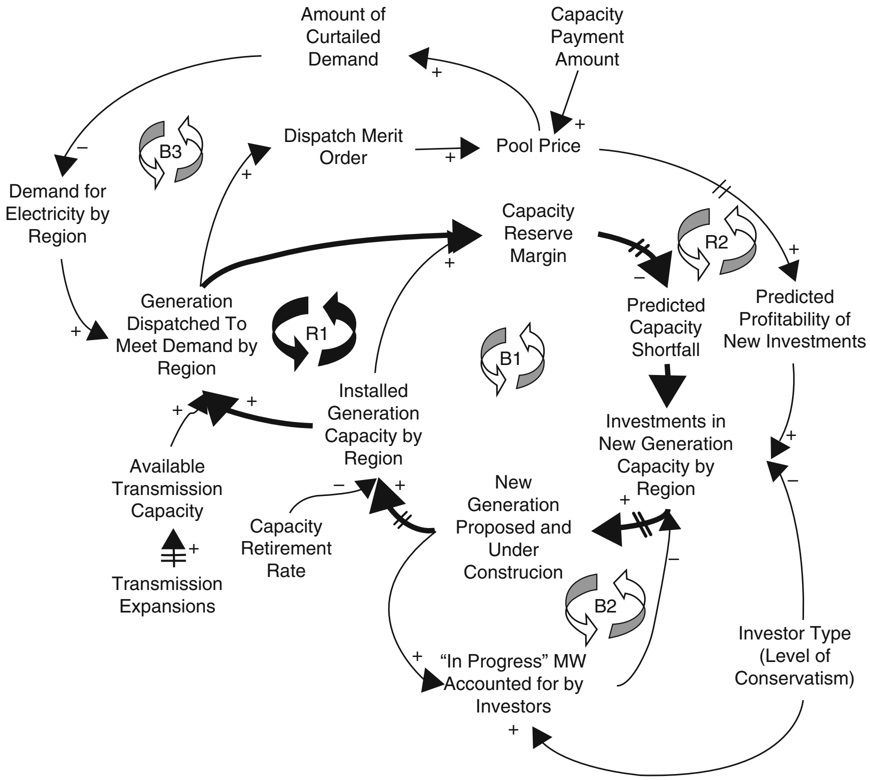

Fig. 14.6 Causal loop diagram: showing all five feedback loops

this aspect of the model had the goal of testing a more formal and widespread consumer response to price spikes.

A second intervention strategy incorporated into the B3 loop was a continuous capacity payment (CCP) that would provide additional incentives for investors to bring capacity online earlier by providing additional revenue to cover the capital and other fixed costs not covered by the energy price. The CCP helped to spread the costs of price spikes over all hours of the day and over each day of the year.

14.3.2 *Modelling Investor Behaviour*

Following Ford (2001) three types of investor behaviours were included in the APPCON Model. The first group were the *believers* who are the most aggressive in that their investment behaviour ignored all power generating capacity that had been either approved or was under construction. *Precounters* were the most rational or

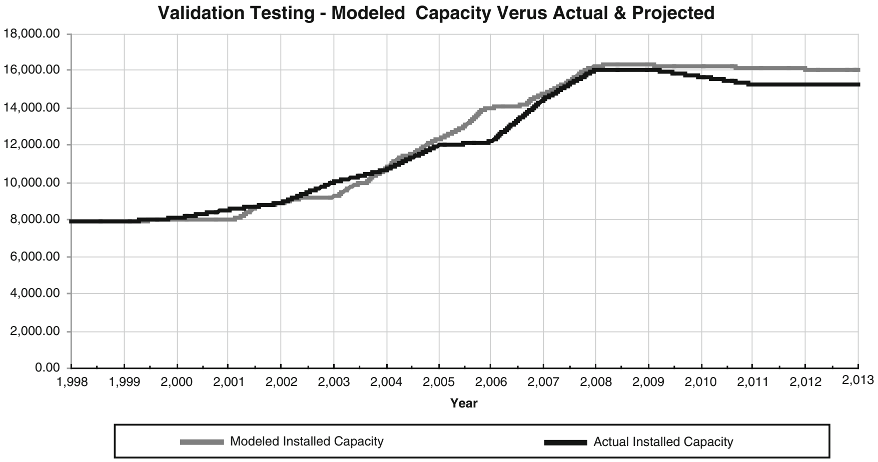

Fig. 14.7 Validation of the base case scenario with capacity additions (90% fit)

conservative of the investor types modelled in that they took into account all capacity that was on hold, under approval or under construction. Finally, the third group of investors were the *followers* who exhibited a “herd mentality” or the “flocking” behaviour discussed by Waldrop (1992, p. 42). These investors would only commit after others had invested in plants that were already under construction.

Figure 14.7 shows one of a series of validation runs (see Seel 2004, for others) in which a base case scenario is projected into the future and additional capacity is added to the system. Over the historical record the model provides a 90% fit. Three experimental scenarios were initially explored: 100% precounters, 100% believers and a 50:50 mix of followers and precounters. The simulations were carried out over a 15 year time period using four time steps per day. The approval process took 12 months for all gas fired generation, 24 months for coal fired and 6 months for wind turbines. With gas and wind turbines 5% of the applications were refused while for coal this figure was 10%. Delays prior to construction were built into the process, 3 months for wind, 6 months for gas and coal fired generation. Construction itself took 6, 18, 36 and 48 months for wind, gas, cogeneration and goal power plants, respectively. Energy imports were set at 800 MW from British Columbia and 150 MW from Saskatchewan. All figures were based on historical analysis and experimentation and sensitivity analysis of earlier runs of the simulation model for the recent historical record.

14.3.2.1 Results of the Simulations

For the 100% precounter scenario there is a correction in the southern Alberta (SAB) region in 2003 and then capacity comes online in a steady progression similar to what was expected under the null hypothesis shown in Fig. 14.1. The 100% believers' scenario exhibits two construction booms, the first in 2002–2005 and the second in 2011–2013. The mixed scenario with an even split of followers and precounters produces a huge boom in the years 2002–2003 and then an "echo" in 2006–2007.

Investigations of the product mix using the base case scenario exhibited a long "golden age" for gas up until 2007 and then a re-emergence of coal as a primary method of generation for the baseload.

The 2000–2001 price spikes occurred in all scenarios and are perhaps unavoidable but the presence of investors that assumed the follower behaviour caused the greatest dampening of the spikes while precounters resulted in the highest overall prices. Using a $10 per megawatt capacity payment produced the smoothest introduction of new capacity ahead of demand. The complexity of the behaviour of the system is revealed by the fact that values either above $10 or below this figure had little effect in smoothing out the price spikes.

Most interesting of all was the introduction of price sensitive demand into the model. This resulted in up to 750 MW of load being curtailed in the peak demand periods in 2001 and 2003 using the base case scenario. Consequently there was a much smaller, delayed construction boom that required almost 1,600 MW less capacity by 2013.

14.3.3 Discussion

It appears likely that something similar to the rational, precounter mindset was initially anticipated when conceiving Alberta's deregulated power generation market. However, the APPCON model has shown that the presence of other investor behaviours can have a dramatic effect on market evolution and result in varying degrees of boom and bust cycles. The boom-and-bust outcome, and thus the alternative hypothesis (Fig. 14.2), was shown to exist for the base case scenario and also when it was modified with the believer and precounter: follower scenarios. The desired, null hypothesis (Fig. 14.1) that avoided the boom and bust oscillations was produced in the 100% precounter scenario and in the base case simulation that introduced capacity payments.

Rhetorically, our first research question may be posited again: why did investors fail to bring into production capacity that would take advantage of the extremely high prices that emerged in the year 2000 and later. The answer appears to be that the price spikes that occurred in 2000 and 2001 were unavoidable due to the long lead times that were required to construct new capacity in the post-deregulated market. It may be concluded, in concert with Ford (1999b), that the momentum of previous energy policies and the long delays before new remedies become fully effective implies that short-term supply problems and price volatility during the transition process cannot be solved but may only be weathered.

The second research question asked whether investors would bring online new power plant generation in a smooth and steady flow. The APPCON model showed that the market exhibited counter intuitive behaviour, or a "surprise" element, and that the boom-and-bust cycles could be mitigated through the use one of the following two strategies: first, a capacity payment of $10 per megawatt or second the introduction of conservation strategies by consumers in periods of peak demand (such a strategy assumes that the consumers are informed of the cost of electricity at all times).The ability of system dynamics models to yield results that have this surprise component is one of their most useful features (Forrester 1991; Mass 1991; and see Thompson et al. 1990, for a typology of surprise).

14.4 Conclusion

This chapter has reviewed and examined past studies of complexity in the social sciences with particular emphasis on those applications in geography where the ramifications of differences in behaviour across space may be significant. In the second part of the chapter one of the most promising methodologies discussed in the first part, system dynamics, has been extended to incorporate spatial variations in the deregulated market for electrical power in Alberta, Canada. This market exhibits many of the characteristics of those systems described in the discussion of complexity, including positive and negative feedback loops and counter-intuitive behaviour. A spatially explicit, system dynamics approach allows for an understanding and remediation of undesirable aspects of the price responses of this system. It is hoped that such approaches are a way forward for research in other systems that resist traditional, reductionist forms of analysis.

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References

Alberta Advisory Council on Electricity (2002) Report to the Alberta Minister of Energy. Edmonton, Alberta

Arthur WB (1989) Competing technologies, increasing returns, and lock-in by historical events. Econ J 99:116–131

Arthur WB (1996) Increasing returns and the New World of Business. Harv Bus Rev 74(4):100–109

Batty M (2005) Cities and complexity: understanding cities with cellular automata, agent-based models, and fractals. MIT Press, Cambridge, MA

Batty M, Longley P (1994) Fractal cities: a geometry of form and function. Academic Press, New York

Baumol WJ, Benhabib J (1989) Chaos: significance, mechanism and economic applications. J Econ Perspect 3:77–105

Bennett RJ, Chorley RJ (1978) Environmental systems: philosophy, analysis and control. Methuen, London

Berry BJL (1991) Long-wave rhythms in economic development and political behaviour. The Johns Hopkins University Press, Baltimore, MD

Black P (2007) Big O notation. Dictionary of algorithms and data structures. Online at: http://www.nist.gov/dads/HTML/bigOnotation.html Accessed: July 14, 2007

Boschma R, Martin R (2007) Editorial: constructing an evolutionary economic geography. J Econ Geogr 7:537–548

Burghes DN, Borrie MS (1981) Modelling with differential equations. Ellis Horwood, Chichester, UK

Carr N (2008) Is Google making us stupid? The Atlantic 302(1):56–63

CERI (2002) Electricity price forecast for the Alberta integrated electrical system. Canadian Energy Research Institute, Calgary, Alberta

Clayton D, Waters N (1999) Distributed knowledge, distributed processing, distributed users: integrating case based reasoning and GIS for multicriteria decision making In: Thill J-C (ed) Multicriteria decision-making and analysis: a geographic information sciences approach. Ashgate, Brookfield, USA, pp 275–308

Cole H, Freeman C, Jahoda M et al. (1973) Thinking about the future: a critique of the limits to growth. Clark, Irwin and Co., Toronto

Costanza R, Sklar F (1985) Articulation, accuracy, and effectiveness of mathematical models: a review of freshwater wetlands applications. Ecol Model 27(1):45–68

Costanza R, Voinov A (eds) (2004) Landscape simulation modelling: a spatially explicit dynamic approach. Springer, New York

Crow S (2000) Spatial modeling environments: integration of GIS and conceptual modeling frameworks. http://www.colorado.edu/research/cires/banff/pubpapers/2/

Doak J, Karadimitriou N (2007) (Re)development, complexity and networks: A framework for research. Urban Studies 44:#2, 209–229

EMM (2008) Europe Media Monitor. http://emm.jrc.it/overview.html#labs;accessed July 14, 2008

Ford A (1999a) Modeling the Environment: an introduction to system dynamics modeling of environmental systems. Island Press, Washington, DC

Ford A (1999b) Cycles in competitive electricity markets: a simulation study of the Western United States. Energ Policy 27:637–658

Ford A (2001) Waiting for the boom: a simulation study of power plant construction in California. Energ Policy 29:847–869

Forrester JW (1971) World dynamics. MIT Press, Cambridge, MA

Forrester JW (1991) System dynamics and the lesson of 35 years. Available at: http://sysdyn.clexchange.org/sdep/papers/D-4224–4.pdf

Fotheringham AS, Wilson JP (eds) (2007) The handbook of geographic information science. Blackwell, Oxford, UK

Gahegan M (2007) Mulitivariate geovisualization, Chap. 16 In: Fotheringham, Wilson (eds) The handbook of geographic information science. Blackwell, Oxford, UK, pp 292–316

Geertz C (1973) The interpretation of cultures. Basic Books, New York

Geoffrion AM (1976) The purpose of mathematical programming is insight not numbers. Interfaces 7(1):81–92

Herremans L, Murch R, McKenzie J (2007) The realities and challenges of bringing global perspectives into the classroom through technology, Chap. 1. In: Cooke L (ed) Frontiers in higher education. Nova Publishers, Hauppauge, New York

Hicks JR (1939) Value and capital: an inquiry into some fundamental principles of economic theory. Clarendon Press, Oxford

High Performance Systems (1990) STELLA II documentation. High Performance Systems, Hanover, NH

Hirsh R (1999) Power loss: the origins of deregulation and restructuring in the American electric utility system. MIT Press, Cambridge, MA

King LJ (1993) Book review of Berry, 1991, op. cit. Ann Assoc Am Geogr 83:175–177

Li MX (2009) Predicting the pattern of votes in the 2006 Canadian Federal Election using socioeconomic variables in a multiple regression and geographically weighted regression. Unpublished MGIS Report, Department of Geography, University of Calgary

Lorenz EN (1963) Deterministic nonperiodic flow. J Atmos Sci 20(2):130–141

Lorenz EN (2002) Predictability – a problem partly solved, Chap 3 In: Palmer T, Hagedorn R (eds) Predictability of weather and climate. Cambridge University Press, Cambridge, UK

Manson SM (2001) Simplifying complexity: a review of complexity theory. Geoforum 32: 405–414

Manson SM, O'Sullivan D (2006) Complexity theory in the study of space and place. Environ Plann A 38:677–692

Mass NJ (1991) Diagnosing surprise model behavior: a tool for evolving behavioral and policy insights (1981). Syst Dynam Rev 7:68–86

Mawa JU (2009) Modeling the 2006 Federal Election outcomes with census 2006 variables. Unpublished MGIS Report, Department of Geography, University of Calgary

May RM (1976) Simple mathematical models with very complicated dynamics. Nature 261 (5560):459–467

Mayer L (1990) An introduction to quantitative geomorphology. Prentice-Hall, Englewood Cliffs, NJ

Meadows DH, Meadows DL, Randers J et al. (1972) The limits to growth. Universe Books, New York

Meadows DH, Meadows DL,Randers J (1992) Beyond the limits: confronting global collapse, envisioning a sustainable future. McClelland and Stewart, Toronto, Canada

Miller HJ (2007) Geographic data mining and knowledge discovery. Chap 19 In: Wilson JP, Fotheringham AS (eds) Handbook of geographic information science. Blackwell, Oxford, UK, pp 352–366

Miller HJ, Han J (2008) Geographic data mining and knowledge discovery, 2nd edn. Taylor and Francis, New York

Nijkamp P (2007) Comment, post workshop discussion. Institute Para Limes, Workshop, September 20–22, 2007, Lochem/Barchem, Holland

Nijkamp P, Reggiani A (1995) Non-linear evolution of dynamic spatial systems: the relevance of chaos and ecologically based models. Reg Sci Urban Econ 25:183–210

O'Sullivan D (2004) Complexity science and human geography. Trans Inst Br Geogr NS 29: 282–295

Phillips JD (1999) Earth surface systems: complexity, order and scale. Blackwell, Malden, MA

Postman N (1993) Technopoly. Knopf, New York

Richards A (2002) Complexity in physical geography. Geography 87(2):99–107

Rockwell G (1999) Is humanities computing an academic discipline? Seminar presentation to a workshop of that name held at the University of Virginia in Charlottesville, November, 1999. http://jefferson.village.virginia.edu/hcs/rockwell.html; last accessed July, 14, 2008

Schintler LA, Gorman SP, Reggiani A et al. (2005) Scale-free phenomena in communications networks: a cross-Atlantic comparison. In: Reggiani A, Schintler LA (eds) Methods and models in transport and telecommunications. Springer, Berlin, pp 201–220

Seel KC (2004) 'Boom and bust' cycles in power plant construction: a simulation study of the temporal and geographical aspects of the Alberta competitive electrical industry. Unpublished PhD Dissertation. Department of Geography, University of Calgary

Skupin A, Fabrikant SI (2007) Spatialization, Chap. 5. In: Fotheringham S and Wilson JP (eds) The handbook of geographic information science. Blackwell, Oxford, UK, pp 61–79

Tanney J (2007) Gilbert Ryle. Stanford Encyclopedia of Philosophy. http://plato.stanford.edu/entries/ryle/;last accessed July 14, 2008

Thomas RW, Huggett RJ (1980) Modelling in geography: a mathematical approach. Harper & Row, London

Thompson M, Ellis R, Wildavsky A (1990) Cultural theory. Westview Press, Boulder, CO

Vargish T (1980) Why the person sitting next to you hates *limits to growth*. Technol Forecast Soc Change 16:179–189

Waldrop MM (1992) Complexity: the emerging science at the edge of order and chaos. Simon and Schuster, New York

Waters NM (2005) Transportation GIS: GIS-T, Chap 59. In: Longley P, Goodchild M, Maguire D, and Rhind D (eds). Geographical information systems and science, Second Edition, Abridged, Wiley, New York

Waters NM (2006) Network and nodal indices: measures of complexity and redundancy: a review, chap 2. In: Reggiani A, Nijkamp P (eds) Spatial dynamics, network and modelling. Edward Elgar, Cheltenham, UK and Northampton, MA, USA, pp 13–33

Waters N (2009) The handbook of geographic information science, edited by John P. Wilson and A. Stewart Fotheringham. J Reg Sci 49 (2), 382–5

Waters NM, Hansen CV, Sun H (2007) Web-based GIS to explore media influence and election processes. ESRI Users Conference, San Diego, August 2007; available online at: http://gis.esri.com/library/userconf/proc07/papers/papers/pap_1845.pdf

Watts PC (2001) Heresy? The case against deregulation of electricity generation. Electricity J 14 (4):19–24

Wilson AG (1974) Urban and regional models in geography and planning. Wiley, New York

Wilson AG (1981) Catastrophe theory and bifurcation: applications to urban and regional systems. Croom Helm, London

Wired Magazine (2008) The petabyte age. Wired, 16, #7, 106–121. http://www.wired.com/science/discoveries/magazine/16–07/pb_intro;last accessed July 14, 2008

Wolfram S (2002) A new kind of science. Wolfram, Media Inc., Champaign, IL