Health care: a case of hypercomplexity?

Jonathan H. Klein

Southampton Management School, University of Southampton, Southampton, UK

Terry Young

School of Information Systems, Computing & Mathematics, Brunel University, London, UK

Corresponding author:

Jonathan H. Klein

Address: Southampton Management School, University of Southampton, Southampton SO17 1BJ, UK.

Email: J.H.Klein@soton.ac.uk

Telephone: +44 23 80592554

Fax: +44 23 80593844

Health care: a case of hypercomplexity?

Abstract

This position paper argues that the lack of take-up of management science (MS) modelling in healthcare is a particularly severe example of a more general problem for MS, articulated by many authorities. We relate this severity to the extreme complexity of the healthcare domain, which might be termed "hypercomplexity". We argue that, for a variety of reasons, the healthcare domain is different to other domains in this respect, and we explore the mechanisms by which hypercomplexity might have inhibited the use of modelling within the domain. We conclude with some tentative suggestions for making progress, including the possibility of taking deliberate steps to reduce healthcare hypercomplexity.

Keywords: *health service, complexity, systems*

Introduction

Healthcare services around the world are grappling to improve delivery against heightened expectations and constrained resources. The question we address in this position paper is why modelling tools (including in particular, but not limited to, simulation modelling) such as are the stock-in-trade of the management science (MS) community, have not been successfully applied to healthcare service design, development, roll-out, training and maintenance to a greater extent than the comparatively sparse amount that they have.

The thinking behind this paper has been informed by three large collaborative UK healthcare research programmes, each involving several universities. The MATCH project (2003-2013) has explored questions of value as they relate to healthcare technology, while the feasibility stage of the RIGHT project (2007-2009) was concerned centrally with modelling in healthcare services. Between them, these two projects attracted around £15M of funding, the bulk of it coming from a set of large Research Council grants, and have involved researchers from several universities in the UK (Birmingham, Brunel, Cambridge, Cardiff, Nottingham, Southampton, and Ulster). In addition, both the authors are contributors to the Cumberland Initiative, a grouping of staff from sixteen or more universities, committed to providing research support for the promotion of the greater use of management science, including operational research and engineering approaches, to healthcare.

In the next (second) section of this paper, we briefly rehearse the evidence for the poor uptake of management science modelling within the health care sector. The third section of the paper poses the question: what is different about the healthcare sector? We discuss complexity in the context of healthcare, and suggest that the unique feature of healthcare is the high level of complexity it displays, which we term "hypercomplexity". In the fourth section of the paper we argue that hypercomplexity has inhibited the use of modelling within healthcare. We conclude with some tentative suggestions for progress.

Throughout this paper, we use the term "management science" (MS) to refer also to operational research (OR), with which it is often considered to be synonymous. We understand the distinctive feature of MS to be its use of modelling (both mathematical and non-mathematical) to elucidate the nature of systems, employing a wide variety of methods, including (but certainly not restricted to) simulation.

The limited use of modelling in healthcare management

There is now clear evidence that modelling is used differently and its results implemented to a lesser extent in healthcare than in other sectors. Jun *et al.* (1999) and Fone *et al.* (2003), for example, observe that the application of modelling within healthcare tends to be restricted to fairly stand-alone systems such as clinics or accident and emergency (A&E) departments. More recent studies bear this out: Brailsford *et al.* (2009) find that, although there is "a steadily increasing rate of publication in this field, with simulation and qualitative (soft) methods in particular rising in popularity", nevertheless "overall levels of implementation are depressingly low" (p. 137). Meanwhile, comparison with other sectors (Jahangirian *et al.*, 2010a, 2011) reveals substantially greater applied usage in the military and aerospace domains, and by business and commerce. Only 8% of healthcare modelling papers report on real problems or user engagement, compared with 36.5% of modelling papers in defence and 48.9% in business and commerce (Jahangirian *et al.*, 2010b).

The lack of common and routine use of the methods of management science modelling in healthcare is, we suggest, an acute case of a more widespread phenomenon. Kirby's (2003) history of operational research in the UK up to 1970 tells the story of a discipline that, despite making clear and substantial contributions in a number of industrial sectors, never quite achieved the recognition that its protagonists believed it deserved. A review by Williams (2008) of literature pertinent to the question of what makes successful management science carries within it an implicit explanation of the disappointing lack of adoption of management science that many have noted. He observes that management science met with "mixed success" in the 1970s (p. 250) – and much the same could be said of its progress in the 1980s and beyond.

Complexity and hypercomplexity in health care

Why should it be that the failure of management science to be generally accepted, but instead rather patchily adopted, is particularly accentuated within the healthcare sector? Is there something particularly different about the healthcare sector? Dawson (1999) suggests that the unique thing about healthcare systems is that they are highly complex: she identifies five spheres (industrial, scientific, professional, public, and political) which "create the dynamics of supply, demand and political involvement in health" (p. 11), and argues that, although in other sectors it is quite common to find that any one of these spheres may constitute a source of complexity, healthcare is unusually characterised by high complexity in all five. Other authorities, too, emphasise complexity as a defining feature of healthcare. Cramp and Carson (2009), for example, place emphasis on the very large number and variety of interconnected variables of which healthcare systems are composed, while Clancy and Delaney (2005) argue that healthcare systems exhibit not only this “combinatorial” complexity, but also “dynamic” complexity, arising “when events are trapped in a systems-dense web of reinforcing and balancing feedback loops” (p. 196). Baxter (2010) acknowledges that “the importance of complexity in health care systems is widely recognised” (p. 7), but observes that within this overall consensus there is a range of views on the nature of healthcare system complexity: he contrasts the view of healthcare systems as complex adaptive systems (espoused, for example, by Plesk & Greenhalgh, 2001) which need to be addressed by the methods of complexity science with other, less formal, depictions of healthcare complexity. For Barach and Johnson (2006) the implication of healthcare systems as complex adaptive systems is that they are collections “of individuals who are free to act in ways that are not totally predictable” (p. i10). Runciman, Merry and Walton (2007) suggest that the key differences about healthcare complexity are the diversity of tasks within healthcare systems, the vulnerability of many patients, and healthcare activity patterns, “which often have a great deal of immediate human involvement with high safety-criticality, with respect to uncertainty, and with respect to… lack of regulation” (p. 111).

These general observations on the complexity of healthcare are mirrored in more specific studies. For example, Greenhalgh *et al.* (2010) echo Dawson’s multispherical perspective in their case study of adoption of shared electronic summary medical records, noting the interaction of political, clinical, technical and commercial worlds with the personal worlds of patients, and commenting on “the sheer complexity of the socio-technical network and its embeddedness in wider institutional structures” (p. 8) that they observed. Gabbay and le May

(2010), in their study of the use of knowledge in clinical practice, see clinicians as facing “a complexity of roles and goals” (p. 31) contributing to a complex environment which renders standard structured guidelines for practice of little use. Their model of knowledge creation acknowledges multiple sources (spheres or worlds) from where the knowledge that informs the “mindlines” that support real expert practice comes.

While there seems general acknowledgement of the complexity of healthcare systems, we need to note that the term *complexity* tends to be fairly loosely defined, and means different things in different contexts – and, in particular, within different disciplines. Notably, the engineering community has addressed complexity: systems engineering provides a highly numerate approach to describing and predicting the behaviour of collections of entities. According to Stevens *et al.* (1998), “systems engineering is about creating effective solutions to problems and managing the technical complexity of the resulting developments” (p. 5). To appreciate the systems engineering perspective, the best single point of reference is perhaps the Handbook of the International Council of Systems Engineering (Haskins *et al.*, 2007). Systems engineering adopts a whole-life perspective, with formal methods for capturing the requirements of the various stakeholders, eliciting user needs and perhaps partitioning the different requirements needed by different users. Within a programme management framework, it recognises the value of highly technical tools and methods, including modelling, simulation and prototyping (Haskins *et al.*, 2007, Section 9.6). Over the years, many conceptual and numerical tools have been created to conceptualise requirement and manage development (see, for example, Simpson & Simpson, 2011).

The change in the behaviour of systems with increasing complexity is described by Calvano and John (2004), who note, for instance, how hierarchical relationships which dominate simple systems give way to lateral influences as complexity increases. Similarly, the intuitive link between cause and effect recedes with complexity. Systems engineering has the capacity to address ever-higher levels of complexity by appealing to the concept of systems of systems (Henshaw *et al.*, 2009) – and, indeed, some of the components of such systems may still be on the drawing board, while others are in the field.

Engineering fails or survives on its performance, and systems engineering is a very 'hard' pursuit, focused on design and management of the development process. It is probably fair to say that, while the methods of systems engineering have been developed to a high degree of sophistication, its true successes lie in fields which, though undeniably complex, exhibit a complexity which is tractable in terms of quantitative modelling. To this extent, while many of its concepts and some of its toolsets overlap with those of MS, the engineering discipline places it in a category of its own, and we note the contribution in summarising the wider field.

Sussman (2002), writing from a systems engineering perspective, pulls together a number of views and definitions of complexity. From this, we might distil three levels of complexity definition. The oldest and most traditional level emphasises complexity as being a property of systems which have a large number of components, and a large number of interconnections or interactions between them. This view of complexity corresponds to Clancy and Delaney's (2005) combinatorial complexity, or Senge's (1990) detail complexity. This kind of complexity is that with which systems engineering, and the related disciplines of systems analysis and operational research were originally developed to deal (Checkland, 1981). Such approaches have at their heart quantitative modelling to develop design and problem solutions. A second level identifies the importance of feedback mechanisms and non-linearities that require more sophisticated, but still fundamentally quantitative approaches (such as system dynamics) to deal with them. Both Clancy and Delaney (2005) and Senge (1990) term this dynamic complexity. Finally, a third level of definition acknowledges the psychological, social, political and subjective dimensions of complexity, and at this level it is rarely suggested that purely quantitative modelling is likely to be effective assuming the current state of the art. It is at this third level that the power of systems engineering falters.

A particular feature contributing to the wicked complexity of healthcare systems is the way in which healthcare encompasses both the objectivity of conventional positivist scientific knowledge frameworks (medical and technological) and the subjectively-constructed social world. On the one hand, much of the demand placed upon healthcare systems is characterised by socially-constructed ideas concerning what reasonable expectations of such systems should be, yet, on the other hand, medical healthcare outcomes are in large part determined by objective physical processes. Healthcare systems are, by their very nature, paradigm-spanning.

We note that this diversity of knowledge paradigm in healthcare is in itself a further source of complexity. The healthcare research field is populated by groups of people whose stances are such that their ability to enter into dialogue with one another is limited. Greenhalgh *et al.* (2009) identify four such philosophical positions: positivist, interpretivist, critical, and recursive. Such paradigmatic diversity characterises many research fields, of course. In healthcare, it gives rise to the "vast (but at the same time, ambiguous, conflicting, and incomplete) evidence base that both practitioners and policymakers need some guidance to understand" (Greenhalgh *et al*., 2009, p. 769) and leads to "confused efforts at scholarship" (p. 771) that might further inhibit progress in understanding the field.

It is certainly true that many other domains have the potential to exhibit the level of complexity of the healthcare domain. The environmental domain, for example, has such potential: it clearly spans objective and socially-constructed worlds in a manner similar to the healthcare system, and this, we would suggest, is one of the major sources of complexity in environmental matters. We feel, however, that at present this complexity is unrealised, due to the current relative lack of engagement on the part of most potential stakeholders. Few people feel as strongly about the environment as they do about healthcare. Runciman, Merry and Walton's (2007) observation that a distinguishing feature of healthcare systems is the presence of vulnerable patients within them is highly pertinent: in a country such as the UK, most people are likely to have had experience of such vulnerability in one form or another at least once in their lives, and might expect to in the future, and such considerations maintain healthcare as a live and serious issue for them. Elections are not currently won or lost on environmental issues (though this might change in the future), but they might well be on healthcare issues. This, then, enables us to recognise a further complexifying feature of healthcare: its salience and urgency to many stakeholders. Emergent from Gabbay and le May's (2010) study of clinical practice (though the authors do not themselves make this point explicitly) is the implication that it is the importance of the "complicated everyday situations" (p. 66) which clinicians face – the fact that the outcomes really matter – that means that they cannot safely be simplified by the use of rough and ready heuristics such as standard guidelines.

A final point we would make is that healthcare systems are large (for example, the UK NHS is reckoned to be among the largest organisations in the world). While size is in itself does not equate to complexity, large systems tend to the complex. Much of such complexity arises from attempts to organise large systems in ways which enable their effective and efficient management. For example, large systems acquire complex internal structures in order to create sub-systems of manageable size. In his 1984 classic study, Perrow (1999) attributes the phenomenon of “normal accidents” in large organisations to a combination of interactive complexity and tight coupling, both of which are driven by the perceived need for effectiveness and efficiency.

In the above paragraphs we have, we believe, identified a number of dimensions of the complexity of a domain.   To summarise, these are:

- The number of spheres (industrial, scientific, professional, public, political) which are central to the domain (Dawson, 1999).
- The extent to which the domain is characterised by a mix of both objective and socially-constructed realities (rather than predominantly one or the other).
- The number and diversity of stakeholders whose views and activities are central to the domain, and the salience and urgency which these stakeholders attribute to the issues and concerns of the domain.
- The variety of paradigmatic perspectives from which researchers have attempted to understand the domain (Greehalgh *et al.*, 2009).
- The number and variety of interactive variables (combinatorial complexity – Clancy & Delaney, 2005).
- The density of positive and negative feedback loops (dynamic complexity – Clancy & Delaney, 2005).
- The size of systems within the domain.

We contend that there is strong reason to consider that healthcare systems score highly on all these dimensions, and so exhibit an order of complexity over and above most, if not all, other systems. We might, indeed, describe the healthcare domain as “hypercomplex”.

Is hypercomplexity the key to low modelling use in healthcare?

Hypercomplexity as identified in the preceding section might be regarded as a powerful incentive to use management science modelling as a tool for enhancing understanding and facilitating improvement in the healthcare domain, and we would not disagree with such a rationale. Thus the low use of modelling in healthcare that is empirically observed is rather a puzzle. We argue that, rather than hypercomplexity encouraging modelling, in actuality, precisely the opposite has happened: hypercomplexity has discouraged the use of management science.

Williams (2008) argues that the key to the successful promotion of management science within an organisation is to “capture the attention of the decision makers – particularly senior decision makers – in the organisation”, in order to ensure that management science, and those that do it, are “seen to be useful and valued” (p. 255). In an argument which has its origins in Ackoff’s (1979a) devasting critique of management science, dating back over three decades but still relevant as an account of the shortcomings of management science as it is frequently practised, Williams identifies four requirements that relate to capturing this attention: the need to understand the client organisation (including the nature of the decision processes within the organisation); the need to manage the relationship with the client (including the development of mutual trust); the need to address strategic and recurrent as well as operational and one-off issues; and the need to carry out analysis appropriately (in particular, from a problem-centred rather than a theory-centred perspective). We suggest that, in a hypercomplex healthcare environment, the meeting of such requirements might be, and indeed have been, particularly inhibited.

First, management scientists may have particular problems in understanding healthcare organisations: modellers may fail to appreciate their complexity, and consequently fail to appreciate many dimensions of the problems they would address. A particular aspect of this is that management scientists may have failed to appreciate the complexity of the decision-making processes that typically go on within healthcare organisations. Choo (1998) identifies four different models of organisational decision-making in common usage: *rational*, *process*, *political*, and *anarchic*. The rational model, which assumes that organisational decision-making is "goal directed and problem driven… regulated by rules and routines so that the organisation acts in a manner that is intendedly and procedurally rational" (p. 170), is conceptually the simplest model, and, due both to training and personality of MS personnel, is probably the model that most management science interventions implicitly assume. However, the alternative models, which reflect various combinations of ambiguity, uncertainty and conflict about goals and about the processes by which they might be reached, are likely to be closer to the reality of organisations in the healthcare sector. In healthcare, scenarios with many different stakeholders and interest groups, are common – arguably, indeed, the norm. An illustrative example of such a scenario is provided by Currie and Suhomlinova's (2006) description of how knowledge sharing within a group of healthcare workers interested in gastro-enterology practice within a UK health centre was undermined by professional and institutional divisions among the participants. To act effectively within decision-making contexts other than the purely rational requires skills that may not come naturally to many management scientists. While some practitioners have argued that problem structuring methods (PSMs) are particularly well-suited as tools for dealing with such contexts, either as front-ends to more analytical techniques or in their own right, we would suggest that the success with which a management scientist works with a client organisation is less to do with the nature of the tools ("soft" or "hard") than with the way they are brought to bear upon the issues of interest (Klein, 1994).

Second, managing relationships with clients, and in particular developing mutual trust, is a process that takes time. Healthcare organisations, however, are notable for their turbulence. Organisational structures and their personnel change frequently, largely as a consequence of attempts to manage their complexity, and the ability to build-up long-term, trusting relationships between analysts and clients is thus severely compromised. In turbulent organisations neither analysts nor clients may have the time to learn to appreciate the other's point of view, and in particular this further reducing the understanding that analysts have of their client organisations.

Third, strategic and recurrent issues are particularly difficult to address when issues are complex, and tools are limited to mathematical modelling. The inadequacy of mathematical modelling to get to grips with problems other than operational ones is an issue that has been discussed frequently in the MS literature, and the perceived strategic deficit of management science provided the impetus for the "soft" OR movement of the 1980s that introduced many non-mathematical problem structuring methods, designed to support strategising in complex environments, to the MS toolkit. However, many of these tools remain relatively unused by MS practitioners. MS is still predominantly regarded as a quantitative discipline, and the difficulty that MS has in engaging with strategic problems remains.

Fourthly, the complexity of healthcare systems serves also to exacerbate the tension between problem-centred and theory-centred approaches to problems. Although every problem is unique, in general it may be possible to adopt theory-centred approaches that provide adequate solutions when the problem context is fairly simple and well-understood. In healthcare it is unlikely that many problem contexts are going to be fairly simple and well-understood. Approaches which engage with the specifics of a problem are required. However, as Harper and Pitt (2004) observe, engaging with the specifics of problem situations can lead to the development of one-off models that are "irrelevant to a wider… context" (p. 658). Van de Ven and Johnson (2006) are sceptical of the "knowledge transfer" solution to the gap between theory and practice, arguing that theoretical knowledge "is not in a form that can readily be applied in contexts of practice" (pp. 803-804). Rather, they favour an approach which they term "knowledge production": the production of practice-based knowledge involving, among other characteristics, multiple perspectives and the grounding of problem-solving in reality. Their characterisation of knowledge production has strong echoes of Ackoff's (1979b) earlier recommendations for the practice of management science. Gkeredakis *et al.* (2011), writing in the context of healthcare commissioning, warn, however, that knowledge and evidence "co-produced" in this way is likely only to be of value if its practical use is considered, and that practitioners "may need to consider enriching the ways they portray the complexities of practising healthcare management" to policy makers and researchers.

We argue that, for the reasons outlined above, management science as it is conventionally practiced has encountered a particularly strong barrier in the hypercomplexity of the healthcare domain. The barrier operates in two ways. First, management science has found it difficult to gain a foothold within healthcare organisations. Second, where such footholds have been gained, management science interventions in healthcare have proved disappointing, focused on the operational rather than the strategic, and limited to isolated systems. Such experience has tended to discourage both sides – clients and providers of management science – from further activity.

Conclusion

The difficulties that management science has had throughout its history with take-up by potential clients is one that has been addressed in the MS literature. Our perspective in this position paper is that these problems are increasingly exacerbated as the complexity of problems increases, and thus, in healthcare, which, we have argued, is an order of magnitude of complexity greater than other domains, the difficulties are particularly serious. It is important to recognise that the underlying reasons for these difficulties are not intrinsic to management science at its current state of development. Rather, they are due to the way in which it is practiced, and perceived to be practiced. Alternative understandings of organisational decision-making to the rational model have been well-articulated. Alternative approaches to mathematical modelling, and modelling methods which seek to accommodate complexity and its implications, have been developed. Alternatives to theory-centred approaches exist. Management science could adopt such alternative perspectives more whole-heartedly. This seems a more realistic way forward than expecting healthcare organisations to change into entities more suited to the traditional way of MS.

At the same time, we might question whether healthcare systems need be as complex as they are. We have outlined the characteristics that we believe contribute to the hypercomplexity of healthcare systems. We might now ask: how many of these are necessary characteristics? Clearly, some follow from the demands of a pluralist society in which consensus policy-making is no longer compatible with the beliefs of most members of society. Totalitarian healthcare systems would have much of their complexity legislated away.

Following Perrow's (1999) observations, one aspect of healthcare systems which might be manageable is their interactive complexity and tight coupling. We are not advocating the breaking up of the NHS, but we are arguing for exploring the potential to substantially decouple many of its subsystems. The push towards an integrated healthcare system has been driven both by the perception that the technology exists to make such integration feasible, together with the recognition of the efficiency savings such integration could realise if implemented successfully. However, integration does not have to imply high interactivity and coupling, and and the flexibility and manageability that come from a less tightly-coupled system have the potential to provide better value for money, particularly if modelling is used more extensively to address the design of such a system.

We entirely accept that the thrust and conclusions of this position paper are to some extent speculative. There could be other reasons for the lack of adoption of MS which we observe. For example, simple lack of access to MS, unavailability of training in its use and implementation, and cultural features of the healthcare sector, could, and probably do, all play their part. Exploring such reasons by means of empirical study of the use and implementation of MS modelling within healthcare organisations would be useful. At present, such considerations are beyond the scope of much healthcare research. For example, a recent review by Guerriro and Guido (2011) of management science as applied to operating theatre management makes no mention of the extent to which the work reviewed was implemented. Studies which focus on the use and implementation of the results of MS modelling in particular (as well as, more generally, the use of other forms of evidence, in healthcare decision-making should be welcomed. For example, the study by Brailsford *et al.* (2013) on the barriers and facilitators to the use of a simulation modelling tool reports on a number of factors that relate to hypercomplexity as we have characterised it, though this line of argument is not explicitly developed.

In summary, while our position is that the challenges posed by the hypercomplexity of healthcare are effectively unique, we also believe that management science is in principle capable of rising to this challenge. We are suggesting three ways forward: a focus on further developing an MS fit for the purpose of addressing hypercomplexity; an exploration of the extent to which “de-complexifying” healthcare systems is feasible or desirable; and empirical study of the implementation of MS modelling and other sources of evidence within the field of healthcare.

Acknowledgements

The authors are grateful to the two referees appointed by the journal for their helpful and insightful comments on the original submission of this paper.

References

R. L. Ackoff (1999a) The future of operational research is past, *Journal of the Operational Research Society* 30 (1979), 93-104.

R. L. Ackoff (1979b) Resurrecting the future of operational research, *Journal of the Operational Research Society* 30 (1979), 189-199.

P. Barach & J. K. Johnson (2006) Understanding the complexity of redesigning care around the clinical microsystem, *Quality & safety in Healthcare* 15 (2006), i10-i16.

G. Baxter (2010) White paper: complexity in health care. The UK National Research & Training Initiative in Large Scale Complex IT Systems, 2010.

S. C. Brailsford, T. B. Bolt, G. Bucci, T. M. Chaussalet, N. A. D. Connell, P. R. Harper, J. H. Klein, M. Pitt & M. Taylor (2013) Overcoming the barriers: a qualitative study of simulation adoption in the NHS. *Journal of the Operational Research Society* 64, 157-168.

S. C. Brailsford, P. R. Harper, B. Patel & M. Pitt (2009) An analysis of the academic literature on simulation and modelling in healthcare, *Journal of Simulation* 3 (2009), 130-140.

C. N. Calvano & P. John (2004) Systems engineering in an age of complexity. *Systems Engineering* 7 (2004), 25-34.

P. B. Checkland (1981) *Systems Thinking, Systems Practice,* Wiley, Chichester, UK, 1981.

C. W. Choo (1998) *The Knowing Organization : How Organizations Use Information to Construct Meaning, Create Knowledge, and Make Decisions,* Oxford, New York, USA, 1998.

T. R. Clancy & C.-W. Delaney (2005) Complex nursing systems, *Journal of Nursing Management* 13 (2005), 192-201.

D. G. Cramp & E. R. Carson (2009) Systems thinking, complexity and managerial decision-making: an analytical review, *Health Services Management Research* 22 (2009), 71-80.

G. Currie & O. Suhomlinova (2006) The impact of institutional forces upon knowledge sharing in the UK NHS: the triumph of professional power and the inconsistency of policy, *Public Administration* 84 (2006), 1-30.

S. Dawson (1999) Managing, Organising and performing in health care: what do we know and how can we learn? In: A. L. Mark & S. Dopson (1999) *Organisational Behaviour in Health Care: The Research Agenda*. Macmillan, Basingstoke, UK.

D. Fone, S. Hollinghurst, M. Temple, A. Round, N. Lester, A. Weightman, K. Roberts, E. Coyle, G. Bevan & S. Palmer (2003) Systematic review of the use and value of computer simulation modelling in population health and healthcare delivery. *Journal of Public Health Medicine* 25 (2003), 325-335.

J. Gabbay & A. le May (2010) *Practice-Based Evidence for Healthcare: Clinical Mindlines*. Routledge, Abingdon, UK, 2010.

T. Greenhalgh, H. W. W. Potts, G. Wong, P. Bark & D. Swinglehurst (2009) Tensions and paradoxes in electronic patient record research: a systematic literature review using the meta-narrative method, *Milbank Quarterly* 87 (2009), 729-788.

E. Gkeredakis, J. Swann, J. Powell, D. Nicolini, H. Scarbrough, C. Roginski , S. Taylor-Phillips & A. Clarke (2011) Mind the gap: understanding utilisation of evidence and policy in health care management practice. *Journal of Health Organization and Management* 25, 298-314.

T. Greenhalgh, K. Stramer, T. Bratan, E. Byrne, J. Russell & H. W. W. Potts (2010) Adoption and non-adoption of a shared electronic summary record in England: a mixed-method case study. *BMJ* 340:c3111 (2010).

F. Guerriero & R Guido (2011) Operational research in the management of the operating theatre: a survey. *Health Care Management Science* 14, 89-114.

P. R. Harper & M. A. Pitt (2004) On the challenges of healthcare modelling and a proposed project life cycle for successful implementation, *Journal of the Operational Research Society* 55 (2004), 657-661.

C. Haskins, K. Forsberg & M. Krueger (2007) *INCOSE Systems Engineering Handbook. Version 3.1*. International Council on Systems Engineering, 2007.

M. J. de C. Henshaw, D. J. Gunton & E. N. Urwin (2009) Collaborative academic-industry research approach for advancing systems engineering. Proceedings of the Seventh Annual Conference on Systems Engineering Research (CSER 2009), Loughborough University, 20-23 April 2009.

M. Jahangirian, T. Eldabi, A. Naseer, L. Stergioulas, & T. Young (2010a) Simulation in Manufacturing and Business: A Review. *European Journal of Operational Research* 203 (2010), 1-13.

M. Jahangirian, A. Naseer, L. Stergioulas, T. Young, T. Eldabi, S. Brailsford, B. Patel & P. Harper (2010b) Simulation in health-care: lessons from other sectors. *Operational Research: An International Journal*. DOI 10.1007/s12351-010-0089-8, 2010.

M. Jahangirian, T. Eldabi, L. Garg, G. T. Jun, A. Naseer, B. Patel, L. Stergioulas & T. Young (2011) A rapid review method for extremely large corpora of literature: applications to the domains of modelling, simulation, and management. *International Journal of Information Management* 31 (2011), 234-243.

J. B. Jun, S. H. Jacobson & J. R. Swisher (1999) Application of discrete-event simulation in health care and clinics: a survey. *Journal of the Operational Research Society* 50 (1999), 109–123.

M. W. Kirby (2003) *Operational Research in War and Peace: The British Experience from the 1930s to 1970*. Imperial College Press, London, UK & Operational Research Society, Birmingham, UK, 2003.

J. H. Klein (1994) Cognitive processes and operational research: a human information processing perspective. *Journal of the Operational Research Society* 45 (1994), 855-866.

C. Perrow (1999) *Normal Accidents*: Living with High-Risk Technologies. Princeton University Press, Princeton, New Jersey, USA, 1999.

P. E. Plsek & T. Greenhalgh (2001) The challenge of complexity in health care. BMJ 323 (2001), 625-628.

B. Runciman, A. Merry & M. Walton (2007) *Safety and Ethics in Healthcare: A Guide to Getting it Right.* Ashgate, Aldershot, UK, 2007.

P. M. Senge (1990) The leader's new work: building learning organizations. Sloan Management Review 32(1990), 7-23.

J. Simpson & M. Simpson (2011) Complexity reduction: a pragmatic approach. *Systems Engineering* 14(2011), 180-192.

R. Stevens, K. Jackson, P. Brook, and S. Arnold (1998) *Systems Engineering – Coping with Complexity*. Prentice Hall Europe, 1998.

J. M. Sussman (2002) Collected views on complexity in systems. Massachusetts Institute of Technology, Engineering Systems Division, Working paper ESD-WP-2003-01.06-ESD Internal Symposium, 2002.

A. H. van de Ven & P. E. Johnson (2006) Knowledge for theory and practice. *Academy of Management Review* 31 (2006), 802-821.

T. Williams (2008) *Management Science in Practice*. Wiley, Chichester, UK, 2008.