

COORDINATION AND CONTROL OF LARGE-SCALE COMPLEX IT SYSTEMS: AN INTERDISCIPLINARY REVIEW OF THE LITERATURE

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1. INTRODUCTION

Since the emergence and widespread adoption of computer networks in the 1990s, developed societies have grown increasingly dependent on complex software-intensive systems. Such systems underpin business-critical applications in domains ranging from health care and financial markets to manufacturing and defence, where failure would have profound social and economic consequences Sommerville et al. (2012). These large-scale complexes IT systems are usually created and evolved dynamically through the integration of independently built and controlled heterogeneous components. They tend to be beyond conventional measures of software engineering in terms of numbers of lines of code, numbers of users with different purposes, and level of interdependencies of each component Northrop et al. (2006). This presents an extraordinary set of challenges for understanding, analysing, and predicting system behaviour, because traditional techniques of system development, which assume complete control over the parts of a system, appear inadequate in supporting critical safety, security and business requirements (Calinescu and Garlan, 2012).

It raises questions of coordination and control of systems that involve tens or hundreds of thousands of human users, interacting with tens of hundreds of thousands of interconnected computers. To coordinate and control the complexity of these socio-economically critical super-systems, there is a need for better technical tools and methods of systems development. Yet it is also essential to advance our understanding of the human, social and organisational issues that affect the procurement, development, deployment and use of large-scale complex IT systems (Cliff and Northrop, 2012). It makes the issues surrounding coordination and control of systems a particular interdisciplinary challenge that is beyond the conventional divisions of academic disciplines.

This article aims to review various notions of coordination and control that are relevant to large-scale complex information systems from a range of angles, which roughly correspond to the disciplines of computer science, engineering, sociology, politics and economics. Based on a review method used by social scientist Perri 6 (2004), it aims to provide an overview of the ways in which coordination and control is discussed across these different fields and disciplines. Rather than merely describing existing methods or techniques themselves, this article aims to highlight the assumptions that people working in those areas make about the ways in which coordination and control is achieved in large-scale complex systems. It aims to trace different assumptions across these areas and how these partially relate to one another.

The article commences with a review of how in computer science and systems engineering complexity in large-scale IT system is dealt with, by focusing on a range of modelling approaches. This is followed by a review of organisational coordination and technological integration in the fields of sociology and politics, in terms of issues such as standardisation, boundary objects, multiplicity across network space, and governance. Finally, this article discusses economic issues relating transaction costs and techno-economic lock-in situations that

are relevant to large-scale IT systems.

2. COORDINATION AND CONTROL THROUGH MODELLING

Abstract models such as computer or computational models, which simulate a system are used to explore or estimate the performance and behaviour of systems that are too complex for mathematical expressions in analytic form. The common approaches to modelling are either based on processes, data or autonomous agents, with simulation models often addressing a specific problem within a particular discipline. In the natural sciences process-based simulations tend to be preferred, whereas in the social sciences agent-based approaches are most likely. However, simulation models that are developed as monolithic applications within the confinement discrete academic disciplines might not no longer be suitable for the increasing level of complexity. Hennicker and Ludwig (2012) suggest there is a need for interdisciplinary modelling and integrative simulation to understand better the complex, mutually dependent processes occurring in nature and in socio-economic systems, which for example would be required in modelling the natural and social environment in terms of global climate change. Similarly computer-based simulations as means of studying possible scenarios that may occur in complex socio-technical systems, such as financial market systems, face the specific problem of an increase in heterogeneous elements. Cliff and Northrop (2012) argue that simulating the technical entities in socio-technical systems in itself is a considerable challenge; yet, simulating the social entities is almost always even more problematic. The frequent present of social entities in a socio-technical system, whether individual human agents, or groups of humans operating and interacting as teams or large organizations, entails roles and responsibilities with levels of flexibility, adaptability, and subtleness that are beyond the capability of automated systems.

Although Cliff and Northrop (2012) point to the work of Outkin (2007) that envisages complex- adaptive-systems, evolutionary agent-based, predictive simulation model, the increase in scale and complexity required to model segments or indeed the entire global financial market system would be unprecedented. Computer science and software engineering to some extent is well equipped to model the autonomous agents – that is constituting entities of a system that function continuously and without constant guidance or intervention in an environment that is physical and at least partially unpredictable (Shoham, 1993). Such agent-based modelling approach is characterized by an absence of perfect scenarios, homogeneous agents, and long-term equilibrium. It offers distinct advantages to conventional simulation approaches, particularly in situations where there is (a) a natural representation as agents, (b) decisions and behaviours that can be defined discretely, (c) agents have a spatial component to their behaviours and interactions, as well as when there is (d) an emphasis on agents adapting and changing their behaviours, (e) learning and engaging in dynamic strategic behaviours, (f) when the past is no predictor of the future, or (g) when scaling-up to arbitrary levels is important (Macal and North, 2006). It allows to either specify the behaviour of agents through a normative model for developing a simpler and more descriptive heuristic model of behaviour, or to develop formal logic frameworks that reason about the behaviour of agents (Macal and North, 2006). Coordination in this form of modelling rests on the general premise that agents have a capacity to make independent decisions that relate to other agents within a system.

It is this “autonomy” of agents that implies the possibility of “infinite” configurations of the relations between agents, which makes agent-based modelling a suitable approach to capturing

emergent phenomena. According to Bonabeau (2002), emergent phenomena result from the interactions of individual entities, which cannot be reduced to the system's parts, as 'the whole is more than the sum of its parts because of the interactions between the parts. An emergent phenomenon can have properties that are decoupled from the properties of the part.' (ibid. 7280) It is this characteristic that makes a system and its components difficult to understand and predict. This is particularly relevant for large-scale complex information systems, as the more interrelated agents within a system, the more like it is for phenomena to emerge that are beyond the individual components. Proponents of agent-based modelling, such as Bonabeau, argue that the produced representations of this kind of modelling approach are more natural to describe phenomena than to come up with equations that represent the emergent phenomena. Although Bonabeau (2002) concedes that equations can in principle represent any form of behaviour, the complexity of differential equations in so-called equation-based models increases exponentially as the complexity of emergent behaviour increases.

Either way, sophisticated non-deterministic models such as those based on Markov chains (e.g. Benveniste, Fabre, and Haar, 2003), have been explored in the research field that studies the adaptive behaviour of humans and synthetic agents in predictive simulation models of distributed and concurrent systems, such as large complex networked systems. Proponents of this approach argue that models based on mathematical equations however are not subject to the significant practical issues that tend to constrain the agents-based modelling approach for large-scale system. Simulating the behaviour of all of the components within a system can be extremely computation intensive and therefore time consuming. Although computing power continues to increase, the high computational requirements remain a problem when it comes to modelling large-scale systems that continuously adapt to the changing environment. It might be suggested that modelling some existing large-scale complex information systems would require computation time—with the current computation power—in the order of millennia if not exceeding the lifespan of the universe. In this way, the formalism and the mathematics behind game theory have increasingly become significant in computer science as a method to deal with the stochasticity of agents' behaviour within complex dynamic systems. For example, the research on organisation and coordination within so-called multi-agent systems, by Messie and Jae (2005), introduces techniques from game theory to produce self-organising, polymorphic, lightweight, embedded agents for systems scheduling within a large-scale real-time systems environment. This approach facilitates optimum real-time scheduling through the emergent behaviour of thousands of agents.

Although overcoming the practical problem of limited computational power through equation-based games tends to increase intractability, games are merely one way to deal with random or non-deterministic elements in the interactions between agents. Another way to deal with these probabilistic elements that agents introduce in within a game—that may represents a complex system—is the deployment of Markov models. This form of analysis, based on a stochastic chain or a non-deterministic process with Markov property, is said to yield results for both the time dependent evolution of a system and the steady state of it. Heuristically, Markov chain theory, for instance, provides a model for analysing a collection of random set of variables, in contrast to other models, with a crucial aspect 'that it is forgetful of all but its immediate past.' (Meyn and Tweedie, 1993, p. 3) In other words, the conditional probability distribution of future states of the chain depends only upon the present state and is conditionally independent of past states. This, for example, would allow an application for systems engineering that could understand the probability distribution of transitions that are determined

by a variety of possible events, such as the failure or repair of an individual component within a system.

Such complexity of an integrated information system could for instance be represented in a state diagram that shows the states and predictability of transition within a dynamic system. Such a diagram would consist of nodes that represent a possible state of the system, which is determined by the states of the individual components, connected by arrows that represent the rate at which the system operation transitions from one state to the other. In this way, Markov chains or processes can even be an integral part of agent-based model or game by introducing probabilities, as a way of dealing with a multitude of emergent properties. This however, is not only important for modelling or simulating large-scale complex IT systems, but also for their quantitative verification, an established automated technique that aims to ensure predictability and dependability of software systems, which exhibit probabilistic behaviour through continuous adaptation (e.g. Dräger and Kwiatkowska, 2012)

Continuous change and ongoing adaptation of systems and their components has also been a concern for systems engineering, an interdisciplinary field of engineering that focuses on how to design and manage complex socio-technical systems. In particular, the derivation of requirements for complex systems has been recognized as a major problem. The approaches to modelling specific system requirements is different to equation-based modelling that usually aims to modelling the behavioural characteristics of a system, rather than its requirements. Some authors in the field of software engineering (cf. Dobson, Sommerville, and Dewsbury, 2007; Sommerville, 2007; Sommerville, Lock, and Storer, 2012) argue that behavioural approaches to modelling are inappropriate for the elicitation of system requirements. They assert that in most organization, new systems nowadays are created by integrating functionality from existing systems and components in a multi-agency system of systems. Because systems are mostly never developed from scratch and functionality tends to be pre-defined, Sommerville, Lock, and Storer suggests that it is 'more appropriate to consider the system requirements from an informational perspective – what information should the system provide and who needs that information to do their job.' (2012, p. 266) Such a responsibility models serve as a basis for identifying the stakeholders that should be considered in establishing the requirements and provide a basis for a structured approach to the overall question of coordination and control.

This socio-technical approach to modelling is different to others in system engineering in that they do not foreground classical issues such as risk, which for example is sought to be quantified with the aid of complexity theory (cf. Calvano and John, 2004) or dealt with by survivable and scalable consensus object (cf. Malkhi and Reiter, 2000). It is an approach that beyond questions of merely operationalising models into programming tools, seeks to understand and model the social laws and conventions that govern the coordination of multiple agents, or distributed agent systems (cf. Khunboa and Simon, 2001; Barbuceanu, Gray, and Mankovski, 1999). While technical issues with regard to system dependability are generally considered to be important, authors such as Dewsbury and Dobson argue that 'many failures arise through the interactions of organisations, people and computer systems which are bound together in a socio-technical system' (2007, p. vii) and only through an inter-disciplinary approach, which takes account of the dependability of people, organisations and computers, these problems can be tackled.

3. STANDARD REPRESENTATIONS AND ALIGNMENTS

Like in the field of systems engineering and computer science, in the social sciences there is a strong interest in material and organisational arrangements that constitute systems. Although for many social scientists modelling large-scale complex systems is not a prime concern, most of the current discussion are on issues relating to the representation of systems—e.g. IT systems envisaged or actually deployed in healthcare settings. Keen (2012) for instance argues that generic representations of healthcare systems with the aid of tracing care pathways, could make healthcare provision safer and more productive. Although the use of IT systems in healthcare itself is challenging (Keen, 2006), system developers are increasingly confronted with healthcare delivery that continues to become more complex, by requiring more intensive and more frequent co-ordination between different professionals, across a number of organisations. The complexity of modern health systems in this sense relates to highly modularised care and relatively low levels interdependencies in coordination across specialties.

The high level representation of the ideal journeys that people take through health systems in form of care pathways is a relatively novel way- in line with patient-centered care concepts- that aims to ensure effective coordination between various professions and services and control of patient safety. The representations of care pathways typically take the form of sequences of discrete decisions and actions that are based on recommendations from available evidence from experimental studies (cf. Davis, Rogers, Rudol, Hughes, and Lip, 2007; Pearse, Holt, and Grocott, 2011). Keen (2012) referring to institutional theorists such as Helper, MacDuffie, and Sabel (2000) argues that there are two distinct types of uncertainty in any patient journey: i.e. task uncertainty and environmental uncertainty. With regard to the former, uncertainty relates to clinical practices about the appropriate course of action for a patient, whereas for the latter uncertainty relates specialisation of teams who have own discretion and expertise by everyone across a pathway. Keen (2012) argues that as a consequence of this uncertainty, a patient's journey is never simply a sequences of rational decisions. In other words, decisions taken by both clinicians and patients, who are influenced by organizational arrangements that are shaped by absences and presences of socio-material configurations,. This presumably makes information systems for managing clinical and organisational risks similar in term of the challenges related to developing large-scale complex IT systems.

The envisage healthcare IT systems that focus on dealing with risks, responsibilities, and patient outcomes, rather than merely recording and accounting for clinical activities will be anything else than conventional IT systems that are routinely deployed in healthcare settings. As such they will be large in scale, as they need to operate across entire care sectors, and complex as they will need to deal with high levels of automation for processing and capturing data, high levels of uncertainty as discussed above, and continuous changes as evidence about best practice develops. Arguably this makes large-scale complex IT systems consequential and contestable—meaning that they are effects of standardisation processes that are not necessarily fixed across space or time.

In the social studies of science and technology, it has been suggested that standardisation can reduce local uncertainties. S. Star and Griesemer (1999) and Bowker and S. L. Star (1999) argue that standardisation can facilitate the coordination of heterogeneity that exists within a system. This form of coordination enables a system to respond to different combined agendas and the complexity of the human, technical or organisational world may present. It removes local uncertainties through classificatory objects that exist across dispersed groups or entities.

However, what these authors refer to as boundary objects are themselves supported and metaphorically held in place by other objects that are not necessarily standardised and classified themselves. For example, Bowker and S. L. Star (1999) argue that *International Statistical Classification of Diseases and Related Health Problems* (ICD) as a particular way of classifying causes of death is attributed to a whole range of broader factors, such as Westernisation, industrialisation, and bureaucratisation. Although these broader factors do not describe the details of adapting the ICD, it is this level of abstraction that facilitates its introduction in many different places throughout the world. Put in the context of the work by Latour and colleagues, standards are intermediaries that are facilitated by a multitude of mediators that require continuous efforts or ongoing alignment process and are never totally irreversible (Callon, 1991; Latour, 2005).

The creation of standards that transcend local boundaries, it has been argued almost always involves ways of acting at a distance. According to Law (1992) mobility through space depends on relational manifestations, such as innovations which have calculational consequences for a network and facilitate immutable objects. This however has been subject to controversy; not only may this involve aspects of control at a distance and the colonisation of spaces, but may also spatial limits to the understanding of objects in an array of network relations. Law (2002) argues the assumption that network objects and spatiality underpinned by Euclidean notions of space is questionable. Authors such as Mol and Law (1994) have been pointing to more a complex notion of space and networks since the early 1990's. They suggest standards that vary across regions tend to be the norm and the creation of immutability is extremely difficult. The fact that it is extremely complicated—if not impossible—to cross-compare a relatively simple procedure such as measuring haemoglobin levels for epidemiological or diagnostic purposes across African regions, points to underlying networks such as adequate roads that could safely transport precision instruments anywhere and electricity grids that could power them. Similarly, looking at the history of the ICD it might be possible to get an idea about the incredible effort it takes for standards to emerge at the current scale: more than five decades to be adopted by the World Health Organisation and another 19 years for WHO to stipulate the use of the ICD for mortality and morbidity statistics by all member states.

The work by Law and Mol is useful as it highlights practices of coordination that allow objects to maintain diversity and the ongoing adjustment work it may take to somehow align them within a particular system. According to Law (2002), there are many ways of coordination that allow reconciliation of the various versions of an object produced at different sites- e.g. atherosclerosis in hospital tends to be a *slightly* different than atherosclerosis in a walking clinic. However, such an object partially overlaps and somehow hangs together. As Law (2004) summaries, coordination takes place in form of layering, a strategy that produces singular objects, as for instance symptoms or diagnostic signs that may conflict with one another are distinguished from the underlying condition that is assumed to be consistent. It allows the unification of theories about aetiology of atherosclerosis with its anatomical, physiological and diagnostic expressions that relate to specific possibilities and desirabilities of particular interventions. In contrast to holistic projects, the work by these authors highlights the *reciprocal* referentiality of independent material components. In this way the question of large-scale complex IT systems become an issue of partial connections—how disparate objects somehow connect and hang together in partial ways. Nonetheless, it does not mean that there are indiscriminate sets of differences without links, traces and connections. In other words, compatibility of system components within large-scale complex IT systems can only be forged if there is *something* to

build on that bears the potential of some degree of alignment.

Some commentators argue that large-scale IT systems, in one or another form, could be aligned with various governance requirements. Comfort and Kapucu (2006) suggest that an appropriate information infrastructure may aid inter-organizational coordination in extreme events, or Slayton (2000) and Wiig and Tuell (1996) that a large-scale integration, data collection and information sharing is one crucial for an integrated child welfare and juvenile justice system that promises to increase well-being and reduces levels of abuse and neglect. Although attempts to integrate government structure has always been an key agenda for various governments (Jennings and Crane, 1994), the issue of coordinating public organisations and introducing information large-scale IT systems is not as straight forward as it may appear. Perri 6 (1997) and Perri 6, Leat, Seltzer, and Stoker (1999) argue that attempts to integrate information systems of public organisations in the United Kingdom, occurred as a part of a so-called joined-up government initiative in line with many reform projects that emerged in English speaking countries from the end of 1980s onwards. Arguably it is precisely the bundling together of different initiatives that may initially create momentum, but subsequently may not succeed. Despite an absence of concrete empirical evidence, integrated information technology was also key component of a subsequent transformational government initiative that replaced the policy rhetoric of jointed-up government in the United Kingdom (cf. Cabinet Office, 2005). The planned large-scale patient record system for the National Health Service (NHS) in England that was heralded as the world's largest civilian computer system, was subsequently abandoned in 2013 (Public Accounts Committee, 2013).

There is no shortage of ambitious projects or ideas to introduce large-scale IT systems across various governmental sectors in many countries or even across countries. See for example Su (2005) for an integrated transnational information systems for solving global problems (e.g. disease detection and control, terrorism, and illicit drug trafficking) that would allow sharing and coordinating information and collaboration among government agencies across national borders in South America. Political scientists such as Dunleavy, Margetts, Bastow, and Tinkler (2006) suggest that the governmental initiatives surrounding IT strategies ought to be treated with cautions to disparage the idea of technologically determinist processes of social change. Although these visions may contain many promises, even rather optimist commentators like Dunleavy and colleagues point to the many voices that warn of potentially adverse consequences in terms of data management without adequate individual privacy rights. While some commentators like Hood (1998) seem to suggest governmental reforms that underpin IT strategies are merely fads and fashions, other have shown that the deployment of large-scale IT networks varies across space and can be indifferent to what those how initially developed a system had in mind (Kluser and Banerjee, 2005).

4. ECONOMIC ASPECTS AND COST CONTROLS

There is an established sub-field in sociology that focuses on the nature of the relationships between people, and views these relationships as network-like in nature. The graph-based representations of this type of analysis aim to identify key relationships that are not captured by any conventional organisation diagram. Since the work by Watts and Strogatz (1998) on 'small-world' networks, a large number of researches has been published on the quantitative properties of large scale networks in the physical, biological and social sciences. However, only a small number of studies on large-scale information technology networks that analyses of the patterns

of use of the networks rather than their network topologies, have been reported in the literature on social networks and small worlds. They suggest that the patterns of use of information technology networks exhibit the characteristics of small world networks, i.e. highly locally clustered graphs with short average path lengths.

Within this literature two types of observation can be made. First, both social network analysis and small world methods assume that coordination is achieved through the forging of social relationships of one kind or another. Some researchers interested in small worlds further hypothesise that the growth of large networks is usefully understood in terms of phenomena such as preferential attachment—i.e. the tendency of new members of a network to link preferentially to members who already have a relatively large number of links, rather than to those with few links. In other words, stable large scale social structures can be understood as a product of the ways in which individuals join existing networks. The second observation is that this way of thinking about networks and network growth provides useful points of comparison and contrast become very interested in large-scale information technology systems, and in particular in the Internet, because they have a marked effect on transaction costs.

Typically, studies on information systems assumed that information technology networks have positive effects on market transactions. For example, Malone et al. (1987) argue that networks reduce transaction costs because they allow information to be communicated in real-time, at lower cost than through other means, thereby reducing the cost of obtaining that information. Others like Benjamin and Wigand (1995) discuss how these technologies may reduce transaction costs by decreasing coordination costs within a value chain, or how it could serve as an efficient allocative structure that could bring buyers and sellers efficiently together (Ciborra, 2000). By contrast, Cordella (2006) argues that in certain situations rather than reducing transaction costs IT system may increase them. He highlights the importance of considering the interdependency of factors that contribute to transaction costs when these technologies aim to reduce the effects of transaction costs. Although the evidence is limited, this might be particularly relevant for large-scale IT systems. Records of the failure of the large-scale patient record system for NHS England indicate a financial loss of nearly ten billion pounds sterling (Public Accounts Committee, 2013).

Economists like Varian, Farrell, and Shapiro (2004) suggest that information technology tends to be particularly susceptible to technological lock-in situations, where the value of a good depends on its compatibility within a network with components required to be used in conjunction with others. Even though the Internet is characterised by ease of combining components, through shared tools and protocols, the cost of switching from one service or product to another might outweigh the value of using it. For example, if an organisation has been using a commercial solution for its human resource management for some years, the costs—in money, and disruption—of switching may be too high, even when existing solutions are deemed inadequate. Yet, this is even more relevant for large-scale information technology, as initial investments tend to be considerably greater. Granovetter and McGuire's (1998) analysis of the history of the U.S. electricity industry illustrates how adopted technologies became increasingly irreversible in economic terms as networks expanded. However, other authors in the area of socio-economic have highlighted that well established lock-in situations can create the potential for alternatives to emerge. According to Callon and Rabeharisoa (2008), lock-in situations for economic agents (e.g. developers, producers, distributors, and consumers) can create a basis for the likely emergence of concerned groups that 'decide to embark on investigations that will enable them to explore new options, to define more clearly the problems

facing them, and to seek possible solutions.’ (ibid. 246) For example, the Free Software Foundation (partially behind the GNU/ Linux OS) gained its momentum and intensified in response to MIT licensing code created in its Artificial Intelligence Laboratory to a commercial firm (Krogh and Hippel, 2003). Also evidence is sparse; the most widely adopted software components that underpin the backbone of large-scale IT systems like the Internet are mainly open source, developed by loosely coupled community of programmers without a centralised direction or authority.

5. CONCLUSIONS

This article has reviewed issues surrounding coordination and control of large-scale complex information system. It has provided an overview of key issues across a range of academic fields and disciplines. It has outlined how agent-based, equation-based, and stochastic chain approaches to modelling differ from each other and the advantages and limitations both have as a way of coordinating complex or large scale systems. It showed how models rests on the premise that agents have a capacity to make independent decisions that relate to other agents within a given system, which in turn assumes infinite possibilities and thereby certain levels of complexity. Agent-based models seem particularly suitable to capture emergent phenomena, without exponentially increasing complexity or computation time that equation-based models are prone to. Game theory and Markov chains appear to be a suitable way to deal with random or non-deterministic elements in the interactions between agents that potentially could even be integrated with agent-based models to simulate large-scale complex IT systems. Current socio-technical approaches in systems engineering aim to allow coordination by model responsibilities of agents rather than behaviour. This is a shift away from traditional ideas of controlling risk that invariably introduces elements of uncertainties. This approach to systems engineering appears to require a considerable amount of interdisciplinary research. While the crossover in computer science and various branches of mathematics might be historically well established, the introduction of qualitative methodologies for system context explorations as seen in socio-technical systems engineering are more recent and considerably more interdisciplinary.

Discussion in the social sciences surrounding large-scale complex IT systems have focused on a range of issues. This article has reviewed how organisational and technological standards are a key issue when in dealing with heterogeneity. It showed how large-scale IT systems envisaged in healthcare settings are exposed to uncertainty through clinical and organizational practices and how some forms of standard presentations could affect patient safety and care effectiveness. It also outlined how standards that transcend across space are created and maintained with tremendous effort. This is different from coordination assumes partially overlapping and not necessarily fully aligned multiple objects across space. It also showed how political scientists have shown how organizational or political aims—although often unsuccessful—are the bundled with technological strategies.

Finally, this article discussed how social networks and small world approaches might become relevant in considering economic issues with regard to large-scale IT networks, especially in terms of transaction or opportunity costs and techno-economic lock-in possibilities.

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