Engineering asset procurement: operationalising complex adaptive system theory

Craig W. Furneaux, Kerry A Brown, and Amanda Gudmundsson

Abstract—**Procuring the management and maintenance of engineering assets are key activities of government, particularly given the importance of these assets for business and society. Despite their importance, the most effective methods for procuring engineering assets are still to be determined due to the complexity inherent in such arrangements. While Complex adaptive systems (CAS) theory has been advocated as a coherent theoretical framework for examining both procurement and engineering assets, considerable challenges remain in operationalising this framework for government systems. There are thus two challenges: developing an understanding of the complexity and dynamics of procurement systems, together with a practical problem of how to model such systems. This paper outlines CAS theory and suggests ways that it might be operationalised to examine engineering asset procurement.**

I. Introduction

RECOGNISING the importance of engineering assets to society, many jurisdictions in Australia have developed policies on the strategic management of engineering assets, particularly in order to guide the procurement of asset management and maintenance, which is now typically achieved through private firms. Procuring engineering asset management and maintenance is a critical arena in which to conduct research due to the size of expenditure involved in acquiring and maintaining these assets [1], the typical longevity of the assets, and the significant risk posed to society if these assets were to fail [2]. [3] estimates that over $200 billion will be spent on engineering assets such as transport (roads and rail), ports, utilities (water and electricity) and broadband in the next few years in Australia. Indeed the optimal functioning of engineering assets such as "transportation, energy, information and communication, and water is vital for the economy and society" [2].

As an emerging field of endeavor, engineering asset management (EAM) seeks to optimize the performance of these engineering assets – particularly the whole-of-life management of risks and expenditures for the purpose of achieving organizational goals [4]. While engineering assets are complex technical systems, they are in reality socio-technical systems, and it is argued that research is needed beyond economic and technical aspects of procurement into the broader social, political and environmental context in which the assets are located [2]. The focus of this paper is this organizational context of procurement. Given the relative newness of the field, much research is still needed in order to identify the optimal ways of procuring engineering asset management and maintenance services from the private sector by government [5]. This paper argues that a richer understanding of the procurement of engineering asset management and maintenance services can be achieved by using perspectives from complex adaptive systems (CAS) theory. As a first stage in applying CAS theory to the investigation of the procurement of engineering asset management, this paper seeks to advance how such an application of theory might be operationalised.

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II. Literature Review

A. Complexity and Complex Adaptive Systems theory

Despite significant research undertaken to date, no one predictive tool has been able to predict with certainty the 'best' procurement approach for a given situation [5]. This can be explained due to the technical, organizational and environmental complexity inherent in the procurement of engineering assets [6].

The *technical complexity* of an asset can be determined by the sum of all project elements times the sum of all task and relational interactions [7]. Engineering assets include social, political, economic, and environmental factors, not just technical elements [8], [2], likewise it is argued that engineering assets are not just pieces of technology, but are really socio-technical systems – consisting of both social and a technical elements. The complexity of assets and the way this complexity is handled can have the most critical influences on the formation, development and subsequent performance of the organisations which seek to manage the asset [9].

Organizational complexity is derived from the multiple forms of contractual relationships and compensation formats possible in EAM procurement [5]. The large number of variants of organizational forms, contractual arrangements, forms of finance, together present a rather bewildering array of options for any client [10]. Such variations owe their existence to exploration for better forms of procurement, [11], but the sheer range of choice creates extreme difficulty

in the selection of the most appropriate form of procurement. Even the notion of government as a client is not a simple matter, as government can have multiple roles in EAM projects such as "assessor of infrastructure needs, project manager, facilitator, performance sector, network planner, concession granter, inspector, contract manager, protector of the environment, and representative of the public interest" [12], [23]. Multiple government agencies also likely to have a stake in the outcomes of any given procurement arrangement [13].

External economic conditions also influence government procurement activities as these can influence the timeliness, cost and quality of capital projects [14]. In particular the availability of labor, and the number of potential suppliers of goods and services will affect the costs of individual projects [15]. Government policies in Australia have begun to acknowledge this *environmental complexity*, calling on clients to consider market structures (pure competition, oligopoly, monopoly) when procuring, and the relationships between suppliers [16].

For projects to be effective, technical, organizational and environmental characteristics, all need to be considered when determining the best procurement approach [17]. Put simply: "Procurement is a complex system and cannot be dealt with in a simple, straightforward manner" [18], [51].

An approach which can account for complexity in procurement and holds in every context still remains to be developed [5]. Simplistic and deterministic correlations cannot take into account contextual factors which affect every procurement project, and a systems approach which accounts for the attributes of projects is needed [19]. As [2], [19] argue "new and more intelligent methods are needed … that are able to handle multi-actor, multi-level, multi-objective and dynamic complexity of infrastructural operation".

CAS is a promising line of research for this study as it provides a framework which accommodates the complexity of public sector procurement [20], the engineering assets which are procured [2], and the emergent, changing nature of modern governance arrangements [21], [22] which are required to care for such assets. [8] also argues that the best way to understand the sheer complexity of the social, political, technical, economic factors which affect procurement arrangements requires research to be undertaken from a complex systems perspective.

There is no one theory concerning CAS [23], but rather several theories arising from the studies in a variety of sciences. The following definition will be used in this paper:

A complex adaptive system consists of a large and diverse number of agents that interact in nonlinear and adaptive ways… and the environment as a whole; it is continually adapting in the context of its relationships with other agents [23], [46].

While application of CAS theory to public policy arenas has been held to improve the understanding and performance of organizational systems, considerable work is needed to apply this concept to organizational contexts in general [24], and to public service arrangements, in particular [21],[25].

B. Difficulties in applying CAS theory to the procurement of engineering assets

Bringing a perspective into management from another field can be a fruitful way of developing new theoretical understanding [26]. CAS theory, which has its origins in physics, chemistry, biology and computational studies, may well provide novel and interesting perspectives which can improve our theoretical understanding, provide significant advancement in our understanding of procurement [20] and provide insights into engineering assets. Particularly as CAS offers a framework which enables comprehension of non-linear relationships typical in complex systems [27].

A way forward to the application of CAS theories to organizational research is to begin with some of the insights from the parent domain, and examine their applicability through empirical work, which could lead to novel understandings of social systems, and possibly ways of intervening in them [28]. Such constructs would still need to be tested in order to demonstrate their validity [29]. Significant opportunities are held to exist for the application of systems thinking to public administration [21], [25].

III. Statement of Problem

Procurement arrangements involve technical, organizational and environmental complexity [6]. Ways of handling multi-agents, multi-objectives and multi-levels [2] need to be found. Numerous authors [2], [8], [30] have argued that engineering asset management should be investigated from a CAS perspective. The application of CAS to social systems however, is fairly recent and there are many disagreements about how to apply these concepts [31]. Considerable work is needed to apply CAS theory to organizational systems, particularly the operationalising and modeling of such concepts [21], and the testing of the theory in multiple cases in order to demonstrate and develop the application of the theory to public policy [25]. There are thus two challenges: developing an understanding of the complexity and dynamics of procurement systems, together with a practical problem of how to model such systems.

IV. Statement of Purpose

The purpose of this study then is to examine the operationalising of research into the procurement of engineering assets from a CAS perspective. Such analysis will seek to identify the agents, their roles and interaction; the rules which underlie the system, and the mechanisms by which such systems change and adapt, and are affected by their environment. By demonstrating the utility of CAS to explore the procurement of engineering asset management, the management, maintenance and long-term decision making for asset management is enhanced.

V. OPERATIONALISING CAS RESEARCH IN PUBLIC POLICY CONTEXTS

As noted earlier, an important process in developing an understating of a CAS is to develop a model of the system [32]. Developing a model of a public policy problem as a CAS has been acknowledged as posing considerable difficulty [33]. The sheer complexity of public policy problems, and the large number of agents involved, makes the modeling of public policy areas as CAS very difficult [34]. As a way forward around this dilemma, the elements, components and principles which are held to be part of all CAS will be detailed, together with the operationalization of engineering asset procurement as a CAS.

A. Core elements of complex adaptive systems

Given the newness of the field it is important to build on and expand existing empirical and theoretical foundations [31]. Consequently, this section details those elements which are common in most papers on CAS as applied to organisations and public policy systems (e.g. [23], [24], [33], [35]). These are: 1) Agents, 2) who interact according to schemata, resulting in 3) Self-organization (also termed emergence), 3)Co-evolution, 4) Adaptation, evolution and recombination. These elements are discussed in more detail below:

1) Agents in a procurement system

Rather than approaching complex systems by reducing them to a set of causal variables, CAS models can show how complex outcomes flow from the interaction of agents based on a set of simple rules or schemata [24]. The identification of agents is considered the first step in any CAS study [32]. For organizational researchers, agents can be identified as individuals, groups, or coalitions of groups [24], [219]. An indicative list is provided below:

TABLE I
LIST OF ACTORS IN PROCUREMENT SYSTEMS

Direct		Indirect	
Government	**Private**	**Government**	**Private**
Procurement units Clients Politicians	Principal contractors Sub contractors *(many of these are on pre-qualified supplier databases)*	Policy officers Ministerial advisors	Policy networks Advocacy groups Lobby groups

For this research it is proposed that the main agents in a procurement system can be largely segmented into two groups according to their influence on the decision making process – direct and indirect. Direct agents include government agencies involved in the procurement process, and the firms involved in the planning, delivery and maintenance of specific assets. Indirect agents would be those who seek to influence the decision making process, but have no direct involvement in the decision itself. These include policy advisors, and political lobby groups. In terms familiar with public policy literature, these would be known as policy networks and delivery networks. A complete list requires full analysis of prequalification schemes, and research methods for eliciting the key agents in the system, such as snowball sampling in interview. The interaction between these agents is determined according to the 'rules of the system' which are discussed in the next section.

2) Interaction of agents according to rules (schema)

Often an approach to studying organisations is to identify independent and dependant variables at the same level of analysis in order to demonstrate cause-and-effect relationships. CAS theory approaches this differently, by asking how changes in the rules of agents, or the interaction between agents, result in outcomes for the system as a whole [24]. That individuals use rules to make decisions is reflected in the notion that agents have frames of reference or schemata [32] by which they interpret and evaluate information [21]. Roles and rules are negotiations and gambits in the struggle to define and construct meaning between agents [24]. In fact, CAS can have many competing schemata which compete against each other – the ones that prove to be most salient are the ones that are reinforced [32].

Rules can be classified into two main types – rules which regulate the action of agents, and rules about the system itself [32]. This point is echoed by [35], suggesting that in public policy systems there are rules which focus on the policy arena itself (arena rules), and those which relate to the interaction of agents in a network (interaction rules). Determination of the rules which guide the activity of agents would typically require interviews with the agents of the system. This can be demonstrated in the following Table:

TABLE II
RULES IN A PROCURMENT SYSTEM (ADAPTED FROM [36])

	Description	**Aspects**	**Examples**
Interaction rules	Rules which regulate agents interactions	Access to policy game (who may enter the game, exit options, etc)	Pre-qualified supplier arrangements Institutional arrangements for procurement
		Interaction in policy game (what is permitted or not in interactions)	Conflict Information
System rules	Rules which regulate the setting or policy arena	Reality (what agents consider as core business or quality)	Identity of agents Product rules
		Payoff (costs and benefits for agents)	Status Evaluation criteria
		Positions (positions of agents and relations between positions)	Status Power

3) Choosing between alternatives (fitness function)

CAS theory argues that there are often competing rules in a system, and agents must choose between them [32]. Choosing between alternatives is determined by what is termed the fitness function. Fitness functions govern how the agent will choose among alternative actions [37]. The most appropriate rules, (i.e. the ones that 'work') are the ones that tend to be reinforced – as they have a high level of fitness for agents in relation to the 'landscape'. This concept of a 'fitness function' is similar to the 'logic of appropriateness' outlined by [38], as organisations and individuals make choices based on past experience and learning about what the most appropriate action would be in a given circumstance.

In procurement, little research has been undertaken to date to understand how individual agents choose between differing procurement alternatives in government [5]. In this project, having determined the agents in the procurement system, and the rules they operate by, how the agents make choices between alternative procurement methods needs to be

elicited, which is most likely possible through semi-structured interviewing. CAS theory holds that the order in a system emerges from the interaction of agents based upon rules which are outlined in the next section.

4) Self-organization (also termed emergence)

The structure and dynamics of a CAS are a result of choices by the agents, as they learn and adapt to actions of other agents [39]. In other words there is no formal order imposed from outside of the CAS, and order emerges from the interactions between the agents at a local level [40]. "Emergence is the term used in CAS theory to describe the phenomena of patterns at a higher level of abstraction that arise from interactions among lower level agents" [33],[63]. That a complex process can be self organizing is not new in and of itself. Reference [41] introduced the notion of the 'invisible hand of capitalism' where markets were efficient yet were governed by laws of supply and demand, not government. What is relatively new is the application of this concept to management [41]. Notions of self-organization have parallels in institutional theory with its idea that structures emerge from interaction of agents, as they interpret and use institutional rules [21]. CAS models are inherently multi-level as the order is seen as an emergent property which results from lower levels of aggregate behavior [24]. No application of CAS to public policy has yet been able to demonstrate this multi-level nature of CAS to date. This research project will explicitly attempt to identify the multiple levels involved in engineering assets procurement as part of each case study.

It is argued that "the primary feature of social systems thinking is its focus on those elements that 'emerge' from the interactions of agents and institutions" [25]. The structure of agents interacting in governmental arenas has been of growing concern to public policy researchers – particularly those research the various modes of governance: hierarchy, network and market [42]. Reference [22] argues that these different organizing arrangements are the main mechanisms by which agents in CAS cope with complexity. The effective delivery of government services relies on ensuring the right mix of these arrangements [42]. Unfortunately, the right 'mix' for differing circumstances is difficult to identify. The interaction between the formal (hierarchy) and informal (network) systems produces emergent order, which may or may not be in line with the intentions of those in authority [43]. As [22],[24] argued "administrative networks, shared governance, and co-production of public services developed in the conjunctive state, are real-world examples of the emergent properties of complex adaptive systems".

The implications of the concept of emergence for this research project are that lower levels of interaction result in order at the same level and also higher levels of order. Consequently the interaction of agents is held in CAS theory to result in higher levels of order and this 'emergence' of order should be explored as part of the research project.

Emergence of higher order structures in the procurement arena have emerged in Australia, with the formation of groups such as the Australian Procurement and Construction Council (APCC) and the Australian Asset Management Collaborative Group (AAMCoG). While the APCC does not have executive powers, it provides a forum for "knowledge sharing, intelligence gathering and has the information networks to draw on for formulating solutions" [44], and was established following interaction from state and territory jurisdictions. Similarly AAMCoG exists to facilitate collaboration and knowledge sharing in the area of asset management [45]. A possible view of the emergence of industry characteristics in procurement systems is given in Fig. 1 below.

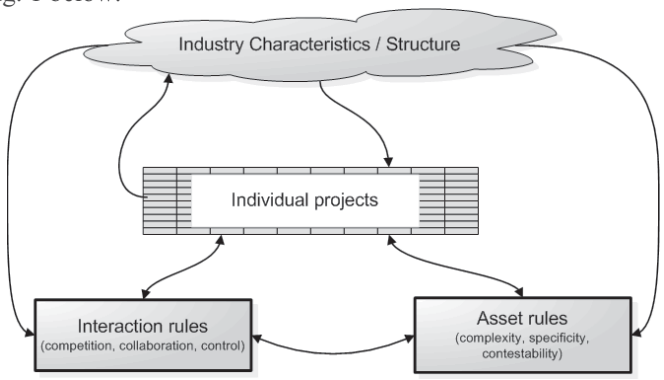

Fig. 1. Emergence in procurement systems

Consequently case studies would also need to explore the notion of emergence in the interviews – seeking to identify higher levels of order, often new institutions or organisations which have emerged from interactions at lower levels of action.

5) Co-Evolution

In a CAS, agents are seen as being interconnected so that the behavior of an agent is influenced by the behavior of other agents in the system. As one agent changes, so does the other – hence the understanding of co-evolution. It is this interconnectedness of agents which distinguishes CAS models from other systems models. The notion of co-evolution has particular purchase for decision making in networks "where experiences and choice influence each other because of learning processes" [46], [9].

One way of applying this to a procurement system is that in organisations and markets, the least-fit element of systems tend to be eliminated – organisations replace their least efficient members, and least efficient firms in an industry tend to go out of business [24]. A new agent drawn at random is likely to have a higher average fitness that the weak one replaces, which sets of changes in relationships between agents and can cause a cascade of changes in co-evolutionary adaptation in the system. With new actors, or new rules, or new relationships between actors, this causes a cascade of changes in the system.

Consequently, changes to the participants in a system, or their rules would need to be examined through interviews and reference to secondary data such as prequalification schemes in order to explore the concept of co-evolution.

6) Adaptation, Recombination, and Evolution

Adaptation in CAS occurs due to changes in the environment, the choices of agents and often a dynamic feedback between these two. When the environment of the system changes, so does the behavior of it agents and as a result, the behavior of the system as a whole – in other words – the system learns and adapts to the new environment [47]. CAS also evolves over time through the entry, exit, and change of agents, as well as changes in the linkages between agents [24]. The structure and dynamics of a CAS are a result of choices by the agents, as they learn and adapt to actions of other agents [38]. [48] argues that learning is a critical issue which is enabled by systems approaches to policy problems.

A CAS perspective would show how the procurement system (the agents, their relationships, and/or the rules) have changed over time, due to either the choice of agents, or changes in the environment. Fig. 3 provides an initial conceptualization of this:

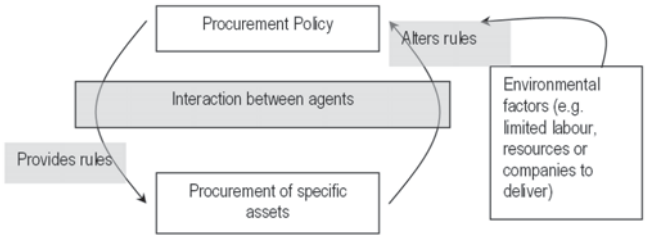

Fig. 3. Adaptation in Policy Systems

In [49] a summary of variant procurement approaches for public works in Australia was advanced. It was evident in this research that many states had recently changed the way they went about procuring building assets [49]. These policy changes were largely driven by interaction with construction firms and client agencies, or by changes in the environment, and resulted in changes to either the interaction rules (how agents interacted) or system rules. Thus while a full investigation of procurement system remains to be undertaken, the dynamics anticipated by CAS theory, are in line with existing research.

VI. Significance

There are two areas of significance for this research: contribution to knowledge in the field, and to practitioners [50].

A. Significance for knowledge in the field

Many procurement approaches assume simple correlations between principal and agent, or cause and effect and consequently may not take into consideration organizational and environmental complexity involved in procurement [6], nor the adaptation, co-evolution and emergence of elements of the system itself. CAS theory draws attention to these dynamics and provides a way of examining the problems involved in these systems. This paper has advanced a way of developing a better understanding of the complexity and dynamics of procurement systems, together with how to model such systems. By demonstrating the utility of CAS theory in explaining the outcomes of procurement systems, a novel theoretical model of policy development processes within government can be developed.

B. Significance for practice

A better understanding of the procurement of engineering assets is likely to lead to a better understanding of how to manage the problems encountered within these systems [43]. If system models are sufficiently accurate, they can move decision makers towards a deeper conceptualization of the impact of their policy choices, and thereby lead to a change in their choices [51]. Improved procurement choices should result in enhanced economic and social benefits for stakeholders. By examining engineering asset procurement from a CAS perspective, it is thus anticipated to advance theoretical and practical knowledge of how such arrangements can be governed and effectively managed.

VII. Conclusion

The procurement of engineering assets is a critical but under-researched activity of government. A chief reason for the difficulties encountered in researching procurement of EAM is the complexity involved in such activities [6]. While CAS has been advocated as a way of examining procurement [20]and EAM [2], challenges exist in how to operationalise such a theory in public policy systems [21], [25]. This paper has addressed these problems by demonstrating how the central elements of CAS: agents who interact according to rules, creating the dynamics of adaptation, co-evolution and emergence [32]; can be modeled in order to investigate procurement systems. It is concluded that CAS provides a way to better understand engineering asset procurement. Better understanding can result in turn in the enhanced management of such assets.

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