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Managing organizational interfaces in engineering construction projects: addressing fragmentation and boundary issues across multiple interfaces

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Extensive and increasing specialization in construction has prompted much criticism—that fragmentation leads to poor performance. Such issues are magnified on engineering construction projects due to their size, complexity, financing, duration and execution by many organizations, often from several diverse countries. Theory, research perspectives and findings of boundary management studies are examined in the context of management of engineering construction projects. The objectives are to investigate theory and practices of boundary management; to examine how boundary management operates on engineering construction projects; and to produce a research agenda for studying further, important aspects of boundary management impacting on engineering construction projects. Conclusions are that the emerging theories provide insights but it is the nature of the markets—notably, the diverse objectives of stakeholders and the procedures and their practices in pursuit of self-oriented benefits—which are the main impediments to achieving greater coordination and collaboration. On complex engineering construction projects, many requirements are emergent and project participants co-evolve to yield self-organizing governance as projects progress within an often fixed formal framework. Recognition of performance interdependence among participants is an essential underpinning of commitment and cooperation; development and use of appropriate boundary management through boundary spanning and boundary objects can foster interaction and coordination even with participants' retention of their individual goals.

Keywords: Boundary objects, boundary spanning, complexity, fragmentation, interdependence, project governance.

Introduction: background and context

Fragmentation is a 'dirty word' in the construction sector. It has been employed extensively in reports as a causal explanation of many of the ills of the industry, most of which relate to alleged poor performance (Latham, 1994; Egan, 1998; Construction Industry Review Committee, 2001). Fragmentation is defined as 'A breaking or separation into fragments' where a fragment is 'a (comparatively) small detached portion of anything; a detached, isolated, or incomplete part; a (comparatively) small portion of anything' (OED, 2010). Such use of 'fragmentation' intentionally carries negative connotations; however, that is not necessarily the reality. By changing the word but maintaining the extant industrial structure, terms such as 'differentiated' or 'specialist' could be employed, each specialism constituting an important fragment; indeed, Adam Smith (Smith, 1789/1970) was an arch proponent of fragmentation in advocating division of labour to enhance productivity, as pursued in 'scientific management' (Taylor, 1911)—a path which construction, and most other sectors (including automotive and aerospace), have adopted with great enthusiasm.

Perhaps the nub of the issue lies in the business relationship changes which stem from the industrial revolution—the transition from craft guilds' masters and journeymen trading with relatively few, known others to

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multitudes of transactions among persons largely unknown to each other. A direct result is the increase in the use and importance of contracts to govern relationships and enforcement of the terms of agreements.

Structurally based concerns regarding fragmentation are addressed by Lawrence and Lorsch (1967) in their treatise on differentiation and integration. Given that technologies are increasingly complicated and that effectiveness and efficiency considerations prompt commensurate differentiation/division of labour/specialization, then the organizational/managerial imperative shifts to integration for the supply of goods and services to ultimate consumers. Hence, acknowledging and respecting the differentiation and the consequent independence of 'component' suppliers lie at the core of integrating those suppliers' contributions and securing their commitment to deliver the final output. Thus, the fragmentation criticism is not one relating to industrial structure primarily, but concerns how integration operates in the market-social context to provide goods and services to customers—organizational and individual behaviour being the core focus, as manifested in both neo-classical (e.g. Friedman, 1970) and new institutional/transaction cost economics (e.g. Coase, 1937; Williamson, 1985).

Specialization has caused differentiation and led to increasingly complex project organizational structures involving numerous specialist firms with each having its own boundary to delineate functional and/or economic activities. Hence, performance of the project organizations, temporary multi-organizations (TMOs) as coalitions (Hobday, 1998), is dictated, to a large extent, by how well the boundary activities are planned and managed, and how permeable the boundaries are (or become) to allow information flow, knowledge sharing, and learning.

The features of engineering construction projects dictate that the degree of separated specialisms is very extensive. The design and construction (realization) processes often require major inputs from various engineering disciplines (mechanical, electrical, chemical, aeronautical, IT, civil, etc.), financial institutions (international and local banks, insurance companies, etc.), management organizations and regulators. (See Greater Gabbard Wind Farm Project, 2011 as an example of the multiplicity of participants in a major engineering construction project TMO.) Many of those specializations remain required during the operating (and adapting) life of the project and during its final disposal (especially nuclear and petro-chemical installations). Thus, clients really 'procure complex performance' (Caldwell *et al.*, 2009, p. 178) through technically and managerially complex projects. Commonly, projects have inputs across many national borders—thereby enhancing the categories of cultural interactions (corporate, professional, national). Thus, understanding how the multiplicity of diverse interfaces may be managed is essential.

Lawrence and Scanlan (2007) review performance on engineering projects and determine eight primary causes of poor performance/failures: 'poor initial planning, lack of clear objectives and deliverables, lack of understanding of dependencies, inadequate resource allocation, poor risk analysis, poor change management, lack of "buy-in" from stakeholders, poor understanding of priorities' (p. 511). Of those issues, at least five can be attributed to fragmentation among project participants. They determine that much difficulty is due to entrenched use of outdated project planning and management tools and techniques which are linear, reductionist and deterministic and cannot cope with iterative working practices (especially design) and the complexities in realizing today's engineering projects. A further, generic issue is inadequate communications between project participants, a problem exacerbated by participant diversity and by IT systems (Flyvbjerg, 2009)—which, often, have significant incompatibilities.

The expanding diversity of specialisms and the geographical and cultural dispersion of engineering project participants add to the problems. An underpinning current of 'silo mentalities', in which persons are reluctant to employ new methods, is common (see Hall, 1982 for further case studies). Clearly, there is much scope for greater effectiveness and efficiency through improvements in intra- and, perhaps especially, inter-group management.

Thus, the research question is: what are important boundaries and how, and to what extent, does boundary management impact on performance of complex engineering construction projects?

Aim and objectives

The aim of this paper is: to explore boundary management on engineering construction projects to address issues of fragmentation and of performance.

The objectives are: to investigate theory and practices of boundary management; to examine the ways and extents to which boundary management operates on engineering construction projects; and to produce a research agenda for studying further, important aspects of boundary management impacting on engineering construction projects.

Methods

The method of study is a critical, exploratory review of theory and literature with particular reference to recent developments (potentially) applicable to engineering construction projects. The widespread criticism based around 'fragmentation' is examined in its major forms (and from alternative perspectives) as a precursor to discussion of the natures of boundaries and approaches to their management. Behavioural issues (in the social-technical system) which affect the relationships of team boundary spanning activities and team/organization performance are addressed together with boundary management from the perspective of complex organizations to identify implications for complex engineering construction projects (such as projects executed through public private partnerships (PPPs) and other forms of joint ventures (JVs)) as well as issues of governance of major engineering construction projects. The discussion addresses the current understanding and practices of boundary management on projects and a research agenda is proffered for advancing enquiry prior to drawing conclusions regarding the aim, objectives and main issues revealed.

Fragmentation and the concept of team boundary

Essentially, the lifecycles of the great majority of construction projects are replete with boundaries which have to be managed. It is not only the realization phase of such projects which incurs TMOs (the 'quasi-firm', Eccles, 1981) but also the occupation and use and the disposal phases. Further, the temporal nature of fragmentation (transient involvements of participants in project TMOs and different participants on successive projects) constrains the acquisition and passing on of knowledge between projects and its capturing by permanent organizations. The occupation and use phase (by far the most protracted and financially significant for the majority of projects) is, now, widely subject to outsourcing of 'facility management' activities, usually including transient involvement of specialist subcontractors for the work required (both construction and building operating related—e.g. security). Thus, construction projects are executed by varying combinations of permanent and temporary organizations, both categories of which exhibit performance which is consequent on the other and, for the constituents of the temporary organizations, is interdependent on the other members of the TMO (see, e.g., Berggren *et al.*, 2001).

The current issues are encapsulated by Owen *et al.* (2010, p. 235) who note that:

> The increased performance requirements and complexity of constructed facilities require additional specialists and increase the need for integration skills. Multi-skilling is rare and document-based thinking is prevalent ... Appreciation of linkages between work products in different functional areas, and the ramifications of this interdependency, is limited.

Thus, this section explores organizational separation and the natures of boundaries of organizations likely to be involved with construction projects, examines managerial issues relating to the boundaries, and discusses the consequences of alternative boundary management approaches.

Fragmentation

Generally, fragmentation has been regarded as occurring along two dimensions—horizontal and vertical. Horizontal fragmentation concerns the multiplicity of actors (individuals, organizations, business units) which carry out functions at, approximately, the same stage of a process (e.g. schematic design of a building). Vertical fragmentation concerns the splitting up of a total process into components/stages which are executed by significantly separated functional actors (e.g. structural engineering design and reinforcement supply and fix). Reports on the construction industry have variously, but consistently, criticized the industry for its fragmentation—Egan (1998) regarding horizontal aspects (at the 'main' contractor level); Higgin and Jessop (1965) regarding vertical fragmentation (that in no other industry is production so far removed from design). The construction industry exhibits extensive fragmentation along both dimensions and, especially for major projects, there is increasingly likely to be extensive fragmentation of the client/customer also—owners, financiers, occupiers, users—plus government agencies and a variety of other stakeholders.

Horizontal fragmentation is common in most industries—the variety of organizations which carry out supply functions. Those organizations differ by type of business unit (but, usually, companies—especially, public limited companies—dominate), structure, size, location and scope. Of some 195 000 private contractors in UK in 2009, 124 employed over 600 people each, while over 181 000 employed fewer than 14 persons each; under 45 000 were 'main trades', including housebuilding, and details are given of both trade and locational distributions (Office for National Statistics, 2010). The Banwell Report (1964) was instrumental in clients of the industry (particularly, public sector) moving from open to selective tendering for constructor selection in endeavouring to secure bidders more suited to the work involved in a project and, hence, both improved performance of project realizations and reduced costs of tendering through less unproductive bidding. Latterly, additional procedures have been incorporated in bidding (notably *curricula vitae* of persons whom the tenderer will use to manage the project construction) and consultant or in-house project managers are employed to oversee project realization as the client's main agent.

Thus, horizontal fragmentation is an industry (structural) phenomenon which must be addressed to foster effective and efficient (competitive?) selection of participants for each stage (vertical) of a project. However, on a project, it is vertical fragmentation (commissioning client, designers, constructors, etc.) and remaining horizontal elements (e.g. subcontractors) where integration (communication, coordination, etc.) through boundary management is required. That project situation is exacerbated by the temporal fragmentation in the TMO, and by the spatial fragmentation of participants.

Organizational boundaries—inter-team and intra-team

In various guises, a great deal of attention is devoted to overcoming boundaries between (sub-)systems, including JVs, PPPs and other forms of alliance between organizations (Sheth and Parvatiyar, 1992), bridging and bonding in the context of social capital (Edelman *et al.*, 2004), supply chains and (social) networks (Cox, 1999), and boundary objects (Bresnen, 2010). Recent perspectives afforded by chaos theory (Stewart, 2002) and by complexity theory (Anderson, 1999; Lucas, 2004, 2005) add to understanding relationships and consequences within systems while other developments, including prospect theory (Kahneman and Tversky, 1979), facilitate appreciation of what is being sought, behaviour, and how evaluations operate.

Drach-Zahavy and Somech (2010) confirm that boundaries are established to separate teams (in-groups) from others such that in-group activities (and management) may be facilitated by some degree of independence (isolation). However, 'because teams cannot internally generate all needed resources, they must engage in boundary activity to protect themselves as well as to acquire resources critical for their survival' (ibid., p. 146). Thus, they posit four boundary activities: buffering—separating the in-group and preserving its resources; bringing-up borders (boundaries)—melding members into a coherent team; scouting—scanning and securing resources from the environment; coordinating—relating to out-groups in the environment with which the in-group is interdependent for success. That demonstrates a 'competing forces model' of independence (differentiation/specialization) and interdependence (integration/cooperation/coordination) in which the forces strive for equilibrium in dynamic environments (akin to Lawrence and Lorsch, 1967).

Frequently, boundary management is examined in the situation of a dyadic interaction concerning how to deal with matters across a single interface—the result of the combination (intersection) of the two individual boundaries. In many organizations, there are both intra- and inter-organizational boundaries and, although intra-organizational boundaries may be mitigated by overarching common objectives, etc. relating to the whole organization, they are, nonetheless, important (such as differences between onsite engineers and office-based engineers—Rooke *et al.*, 2003). In project TMOs, there are not only individual organizational goals/objectives as well as objectives of sub-groups and of individuals but the communicated/perceived project objectives serve, to some extent, as a 'common glue' among participants provided they are clear, communicated and accepted (bringing up borders). The structuring of interactions and, hence, the configurations of boundaries/interfaces is complicated but such complications are mitigated by commitment to common goals—as an essential for teamwork.

Following systems theory ('hard'—Cleland and King, 1983; and 'soft'—Green and Simister, 1999), major features of boundaries are: location (to denote the *system's* content and activities, etc.), flexibility (to change the scope/scale), permeability (concerning ease of movement across the boundary) and effects (changes consequent upon movement across the boundary) (see also Martin *et al.*, 2004).

The location of any organizational boundary lies at the limits of the organization—as defined legally, by its formal systems, or/and informally by its social systems, etc.; however, moving from formal delineation to more informal delineation leads to *fuzziness* in determination of where the limits of the organization lie. That is particularly the case for project activities which generate TMOs for project realizations whether or not formal alliances, JVs, etc. are employed (i.e. buffering). Clearly, the organization's legal boundary is extended if the firm takes over another; it is also extended by entering a formal alliance or JV (flexibility), although differences do arise between equity and non-equity joint ventures (Glaister *et al.*, 1998). However, when a construction firm undertakes a project, the location of the formal (legal) organizational boundary usually remains unchanged but the informal boundary is extended to encompass the project—at least, that organization's role on the project.

A consequence of TMOs is that a multi-tier system of boundaries results—the formal organizations' boundaries; the boundaries around each organization's activity groups operating on the project; the boundaries around each within-an-organization group on the project; and the boundaries around informal groups which include members of different participating organizations. The resultant lack of clarity of *organizational* boundary locations generates potential for overlapping with other organizations on the project also, and so constitutes a notable area of possible conflict (domain/jurisdiction and role conflicts). Otherwise, such arrangements are considered as areas of 'coopetition' (Nalebuff and Brandenburger, 1996), collaborative competition (Kaler, 2009), or competitive collaboration—participants must collaborate to realize the project but do so (somewhat) competitively with each other in pursuit of their own goals in a zero-sum game.

Permeability is demonstrated by ease of movement across a boundary. Construction is an industry with very few, and low, barriers to entry or exit (Hillebrandt, 2000), although certain professions' entry requirements are regulated significantly (e.g. architects in the UK, chartered engineers). Universally, construction (industry, organizations and projects) responds rapidly and extensively to environmental changes (NB price turbulence). Thus, the boundaries are highly permeable.

Boundary effects concern changes which are dependent and consequent upon merely crossing a boundary. In an organizational context, many such effects are behavioural—entering the office of the chief executive officer is likely to result in more polite, if not deferential, behaviour by an employee. Such effects are situational/contingent and, to a significant extent, depend upon organizational cultures, climates and project/workplace atmosphere (Liu and Fellows, 2012). Incompatibility of organizational cultures/climates is likely to generate conflict due to (innocent) inappropriate behaviour, etc.—especially if the persons involved are unaware of/insensitive to such differences (see e.g. Fellows and Liu, 2008).

Owen *et al.*'s (2010) observations, above, articulate the extending complications of projects—which promote increasing specializations, and interdependencies of those specializations in combining to yield complete projects. Commonly, that situation is treated in a reductionist way by splitting a project into manageable components (e.g. a procurement system composed of people, processes; function mechanisms differentiated into project phases dominated by different teams of consultant and/or specialist contractors, etc.) which are analysed individually and the results combined additively (e.g. Reugg and Marshall, 1990; Lawrence and Scanlan, 2007; RIBA, 2008). Thus, holistic/synergistic impacts of component combinations are omitted (Lucas, 2005).

Thompson (1967) determines three forms of interdependencies relating to tasks (or arrangement of work flows). In sequential interdependency, tasks must be carried out in strict order (series); in reciprocal interdependency, outputs of one task are inputs for one or more other tasks, which may cycle iteratively (as in architectural and structural engineering design); in pooled interdependency, each task provides (only) a contribution to the whole and may do so independently (which facilitates parallel working). Thompson (1967) raises two primary questions concerning task interdependencies: what causes task interdependency and who are task interdependent—the answers are contingent in that they are determined by technology and by how the work is organized. Van de Ven *et al.* (1976) extend the debate by adding team interdependencies which may be analysed from both inter- and intra-team (in-group) perspectives. Thus, interdependency may be regarded as a multi-layered phenomenon comprising tasks at intra- and inter-group (team) levels.

In more recent studies, inter-team task interdependence refers to the extent to which a team believes it is dependent on other teams in the organization to carry out its tasks and perform effectively (Hulsheger *et al.*, 2009). The emerging research on inter-team networking typically emphasizes the beneficial role of creating linkages with other teams (Oh *et al.*, 2006; Tuuli *et al.*, forthcoming). In any case, boundary activities should refer to all the interdependent activities that teams engage in to manage their boundaries by relating to external people and objects (Yan and Louis, 1999; Drach-Zahavy and Somech, 2010).

The emergence of team-based project organizations may require shifting the focus from intra-team to inter-team activities in order to understand organizational functioning. According to Drach-Zahavy and Somech (2010), inter-team boundary activity is contingent on inter-team goal and task interdependence, while team heterogeneity, inter-team power relations, organizational culture (individualism-collectivism) and favourable external environment are important moderators of the relationships between inter-team interdependence configuration, boundary activity, team performance and organizational performance. A social identity perspective (Ashforth and Mael, 1989; Brewer, 1996; Hogg, 2000) and interactionism (Mischel, 1977) provide the basis for Drach-Zahavy and Somech's (2010, pp. 146–8) model in which (1) boundary activities are defined as 'team processes necessary to carry out the task at hand that are directed toward external agents in a team's focal environment to gain resources and promote and protect itself' (see also Ancona and Caldwell, 1992; Yan and Louis, 1999); (2) external activities are referred to as 'interactions aimed outside the team boundary' and internal activities are defined as 'intra-team processes occurring within the team boundary, such as forming and enforcing team norms, communication among members, use of internal resources and creation of a shared team vision' (see also Ancona and Caldwell, 1992; Choi, 2002)—forming, storming and norming (Tuckman, 1965); and (3) external team networking is defined as 'those interactions aimed outside the team boundary and directly related to team performance' (see also Joshi, 2006).

Importantly, Drach-Zahavy and Somech (2010) conclude that boundary activity determines whether higher team performance can fully translate into higher organizational performance (in terms of team functioning in the context of interdependent relations with other organizational teams).

Boundary spanning

In the face of global competition, changing economic conditions and increased project (tasks) complexity, there is a greater need for project (organizational) teams to coordinate interdependent work efforts and bridge disconnected teams by managing relationships external to themselves. The team's efforts to establish and manage external linkages (team boundary spanning—scouting and coordinating) can occur within an organization and/or across organizational boundaries. Through team boundary spanning behaviours, teams bridge diverse and disconnected parties and act as critical channels for information transfer and innovation (e.g. Hargadon, 1998; Argote *et al.*, 2003)—which underpins knowledge sharing and social networking.

Boundary spanning, acting across one or more boundaries, is undertaken by persons appointed specifically to do so (designated boundary spanners) as well as by many others doing so informally; often, boundary spanning is analysed and depicted using social network analysis (Di Marco *et al.*, 2010). Boundary spanning occurs extensively between sub-units within a single organization as well as between separate organizations in dyadic and more extensive relationship patterns, including making representations to stakeholders, coordination with other (out-) groups and seeking information from external bodies (Ancona and Caldwell, 1992); such activities are important for performance (Gladstein, 1984) and for innovation (Hargadon, 1998).

Boundary spanning involves bridging—finding and connecting with external organizations which the boundary spanner perceives as being of value—and then bonding to build relationships with those external organizations; similar activities occur to foster internal relationships between sub-units within an organization. Thus, boundary spanning acts to extend and enhance the social capital of the in-group and the organization and, thereby, foster reciprocity and trust, as well as extending the informal boundary of the organization (in-group). However, social capital may also comprise norms of conformity and compliance and, further, may engender stronger boundaries around the in-group which, in consequence, limits external communication and so is detrimental to creativity and innovation through the reduction of novel stimuli (see e.g. Edelman *et al.*, 2004). Demarcation and differentiation of in-group and out-groups is accentuated in collectivist societies (Gomez *et al.*, 2000) thereby necessitating greater effort for boundary spanning.

Marrone (2010) notes that team boundary spanning captures the interactions across the team boundary to parties in the embedding environment such as clients, customers, industry experts and other mutually interdependent teams. Because of the diversity of information obtained through boundary spanning, opportunities arise to negotiate project expectations and requirements between mutually interdependent parties. A particular activity is reconciliation of diverse goals/objectives of stakeholders to yield a coherent and accepted set to apply to the project. Notably, for external cooperation to work well, the organization must have good internal cooperation (Hillebrand, 1996) and, to maximize potential benefits, must operate as a learning organization. (Management and technology transfer (learning) often is an important objective of the host developing country in international JV projects.)

Boundary spanning between different communities of knowledge and of practice involves issues of comprehension and translation between the communities to ensure clarity of meaning (and purpose); such issues are exacerbated internationally with overlays of different languages and cultures. Traditionally, in construction, a primary boundary spanning role is allocated to the engineer on engineering construction projects or to the architect on building construction projects; the particular role (discipline/profession) of project manager, in-house/consultant, is emerging for overall management of projects—notably, the boundary spanning requirements.

In engineering construction projects, recognition of mutual interdependence for performance (and, often, workload) through complementarity of expertise and skills encourages alignment of participants' goals pertaining to (their activities on) the project. For major projects, considerations of physical, financial and risk-bearing capacity engender horizontally configured alliances for spreading and sharing burdens and rewards. However, it is not only goals which must be aligned; there are concerns for appropriate reward allocation and for process compatibilities through sensitivity, tolerance and accommodation, of differing cultures—both organizational and the national cultures in which they are embedded—as manifested in behaviours, languages, rituals, etc. (Hofstede, 2001; Hofstede *et al.*, 2010).

Boundary spanning-in-practice (those who perform boundary spanning—who may, or may not have been so designated) requires that the person(s) becomes legitimate (hence, accepted) in the groups concerned; that may mean that they are fairly peripheral for the specialist activities in each (in-)group but their ability to negotiate relationships between the communities of practice involved is the essence of their role (Levina and Vaast, 2005). Thus, the 'primary task' of boundary spanning is enabling and enhancing flows across boundaries between communities of (differing) knowledge/practice (and interests)—thereby increasing the permeability of those boundaries, reducing boundary effects and rendering informal boundaries greater flexibility.

Boundary objects

It is not only individuals who are involved with boundary spanning but so are various 'objects' (Star and Griesemer, 1989)—which constitute the tools of boundary spanning. Oswick and Robertson (2009) note that boundary objects have both performative roles (indicating what is required—drawing; when—programme; at what quality—specification; and for what price—quotation/priced bill of quantities) and mediating roles (communicating and discursive aspects to aid determination of the final, hopefully jointly developed and agreed, object, e.g. issued design drawings). They note that the mediating roles may operate positively 'as bridges and anchors easing knowledge transformation, change and innovation' (p. 189) but, in other contexts, they may operate negatively 'perceived as generating confusion (mazes) or worse, constraining change and innovation' (p. 189).

Carlile (2002) proposes a typology of boundary objects according to a typology of boundaries of knowledge: repositories (syntactic boundaries requiring common language for communication); standardized forms and methods (semantic boundaries requiring understanding of meaning); and objects, models and maps (pragmatic boundaries necessitating accommodation of diverse goals and interests).

Syntactic differences in knowledge required for tasks which are separated by (organizational) boundaries are likely to involve differences in the types of knowledge (such as a design engineer and a clerk of works). Semantic concerns relate to differences in interpretations (understandings/meanings, e.g. terms of a contract) which may be of degree and/or kind and of particular import regarding differences in tacit knowledge. The pragmatic boundaries are likely to be the most difficult to overcome as to do so requires new practices to be adopted and people prefer the status quo.

There are change (switching) costs in adaptations—involving acquiring new knowledge, validating its applicability, and, if judged suitable, incorporating it into a new knowledge (practice) package; where tacit knowledge is concerned, the process is compounded and is likely to require physical demonstrations of the task executions involved. Further, if knowledge in one field must be translated into a common language for transmission to and comprehension in another field, in which the knowledge (information) may be translated again, there is a significant possibility of information degradation or loss (Grant, 1996), hence the necessity to ensure the appropriate level of express content of the common language—a particular concern for societies which use high context languages.

Thus, Carlile (2002) asserts the three characteristics of effective boundary objects to be 'a shared syntax or language for individuals to represent their knowledge' (p. 451); 'a concrete means for individuals to specify and learn about their differences and dependencies' (p. 452) and facilitating 'a process where individuals can jointly transform their knowledge' (p. 452). The first two facets constitute practical aspects while the third is political. The political facet is important as boundary objects impact on social relations, including status (Bechky, 2003a).

Particular features of boundary objects are that they are susceptible to differing interpretations (plastic) such that they can be understood and used for individual needs—and, thereby, promote interaction, debate and inquiry by diverse communities of practice. Often, those communities of practice access and use boundary objects interdependently on projects, and so those objects must be sufficiently robust to maintain their identity: recognizable structure and data/information content despite different comprehension and use contexts—see Lawrence and Scanlan (2007) for a discussion of programming techniques and autoCAD on engineering projects including their role as boundary objects. Protocols for access to and limits of use of boundary objects—as in BIM—are important, control-based reinforcements of plasticity and robustness on engineering construction projects (e.g. architectural and engineering design inputs).

The balance between plasticity and robustness is essential to the effects which boundary objects may have. Over-extensive plasticity can render boundary objects too vague in meaning and so, too open to vastly differing interpretations—thereby potentially causing frustration as interpretations are too disparate to engender meaningful discussion. Insufficient plasticity renders the boundary objects too rigid—thereby reinforcing differences and barriers, and so fostering independent perspectives and conflicts. Thus, 'The critical feature [of boundary objects] is that they act as common information spaces that enable interaction and coordination without consensus or shared goals' (Bartel and Garud, 2003, p. 333). Hence, boundary objects are essential to the functioning of construction project TMOs, given their multi-objective coalition nature.

'[B]oundary objects' characteristics and performances are embedded in the situated practices of the agents who use them' (Levina and Vaast, 2005, p. 340). Levina and Vaast advocate differentiating between 'designated boundary objects and boundary objects-in-use (2005, p. 340). Boundary objects-in-use are artefacts which are 'locally useful (i.e. be meaningfully and usefully incorporated into practices of diverse fields) and must have a common identity across fields' (p. 341). Thus, boundary objects are representations of knowledge/practice of a community which are used by one or more other communities; the more useful those boundary objects are to the other communities, the more effective and efficient they are.

In many (project) instances there is a multiplicity of boundary objects-in-use which, commonly, associate to form 'boundary infrastructures' (networks of boundary objects, e.g. contract documents) (Bowker and Star, 1999). A common situation is for omissions, discrepancies and divergencies to occur between boundary objects' (e.g. drawings) contents which, for efficient and effective progress, require early detection and resolution. Early detection should be promoted through use of CAD and BIM systems among designers, constructors and project users, provided the system is shared and access is adequate but also that the ability to amend contents is appropriately constrained (see Day, 1996; Lawrence and Scanlan, 2007).

Complexity and project governance

Modern engineering construction increasingly comprises complex projects with multi-stakeholders (Hobday, 1998; Miller and Lessard, 2000; Miller and Hobbs, 2002). Complexity concerns the individual and combinations of technology employed to realize a project and to operate the project in use, as well as the organizations and their assembly on the project. Williams (1999) categorizes project complexity as structure (concerning differentiation: the number of elements, division of tasks, etc.; and interdependency: inter-relatedness/connectivity of the elements) and uncertainty (regarding goals and methods). Not only are engineering products and their realization processes complex but so is the performance package of the project-in-use as required by the client (Caldwell *et al.*, 2009).

Complex adaptive systems (organizations) are characterized by four key elements: (1) agents with schemata; (2) self-organizing networks sustained by importing energy; (3) co-evolution to the edge of chaos; and (4) system evolution based on recombination (Anderson, 1999). For engineering construction projects, the four elements indicate that agents with boundary spanning behaviours organize themselves to locate and import resources necessary for utilization on the project in order to work with other systems in an adaptive/flexible manner, where boundary spanning activities/behaviours and boundary management may result in evolution of new system combinations. 'Strategic direction of complex organisations consists of establishing and modifying environments within which effective, improvised, self-organised solutions can evolve' (Anderson, 1999, p. 216). A particular feature of complex systems is holism—that the performance of the system is not the simple, arithmetic sum of its individual components, but synergy is very likely to operate (Anderson, 1999; Bertelsen and Emmitt, 2005; Lucas, 2005).

Not only do complex projects involve many boundaries around different technologies and organizations, which occur at various levels and differ in nature, but the interdependencies and feedback/feedforward components emphasize the importance of managing across those boundaries. Concerns of such boundary management are likely to be exacerbated as the goals of stakeholders emerge throughout the realization of the project (and, often, beyond) (Thomson, 2011) and the systems themselves co-evolve and self-organize—thereby changing the locations and natures of informal, if not formal, boundaries over the project duration. Hence, it is postulated that boundary management must be flexible and adaptive (responsive, at least) rather than a rigid 'command and control' approach (see discussion of governance, below).

Project organizations as complex systems

A complex system is one made up of a large number of parts that have many interactions (Simon, 1996). Thompson (1967) describes a complex organization as a set of interdependent parts, which together make up a whole that is interdependent with some larger environment. Daft (1992) equates complexity with the number of activities or subsystems within the organization, noting that it can be measured along three dimensions. Vertical complexity is the number of levels in an organizational hierarchy; horizontal complexity is the number of job titles/departments; and spatial complexity is the number of geographical locations. Given the temporal changes in construction TMOs (participants and their agents/representatives), it is appropriate to propose that, especially for major engineering construction projects, a dimension of temporal complexity be added to Daft's typology. Those dimensions of complexity correspond to the dimensions of fragmentation, above, as illustrated in Figure 1.

Since organizations are, often, enormously complex (Daft and Lewin, 1990), the behaviour of complex systems is hard to predict and may be surprising—because it is non-linear (Casti, 1994). In non-linear systems, intervening to change initial conditions and/or one or two parameters a small amount can drastically change the behaviour of the whole system (Anderson, 1999). However, modern complexity theory suggests that some systems with highly differentiated parts can produce surprisingly simple, predictable behaviour, while others which feature simple laws and few actors may generate behaviour that is impossible to forecast. While chaos theory demonstrates that simple laws can have complicated, unpredictable consequences, complexity theory describes how complex causes can produce simple effects (Cohen and Stewart, 1994).

Six important insights of Anderson (1999, p. 217) give a good overview of complexity theory:

(1) 'many dynamical systems do not reach either a fixed point or a cyclical equilibrium';
(2) 'processes that appear to be random may be chaotic, revolving around identifiable types of attractors in a deterministic way that seldom if ever return to the same state';
(3) 'the behaviour of complex processes can be quite sensitive to small differences in initial conditions, so that two entities with very similar initial states can follow radically divergent paths over time' (an important consideration for project performance prediction and control endeavours);
(4) 'complex systems resist simple reductionist analyses, because interconnections and feedback loops preclude holding some subsystems constant in order to study others in isolation'—because descriptions at multiple scales are necessary to identify how emergent properties are produced (Bar-Yam, 1997), reductionism and holism are complementary strategies in analysing such systems (Fontana and Ballati, 1999);
(5) 'complex patterns can arise from the interaction of agents that follow relatively simple rules';
(6) 'complex systems tend to exhibit self organising behaviours: starting in a random state, they usually evolve toward order instead of disorder' (see also discussion of evolving project governance, below).

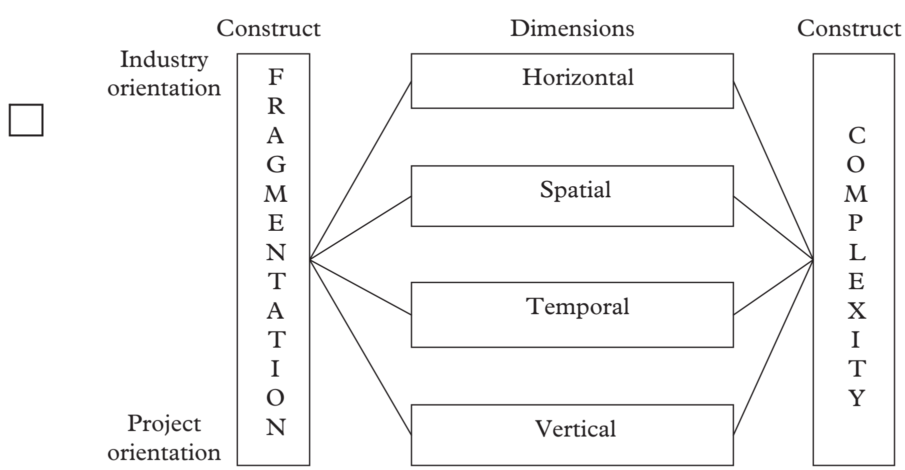

Figure 1 Dimensions of fragmentation and complexity

Complex adaptive systems theories presume that the adaptation of a system emerges from the efforts of individual agents who attempt to improve their own payoffs, but that the individuals' payoffs depend on the choices that other agents make also—typically the case on engineering construction projects involving multi-stakeholders. Hence, agents (project participant organizations and their representatives) co-evolve with one another where local adaptations lead to the formation of continually evolving niches/coalitions (Anderson, 1999) which means that the complex systems do not operate at equilibrium of globally optimal system performance—i.e. value conflicts are resolved as compromises among the multi-stakeholders (through satisficing—Simon, 1996). Morel and Ramanujam (1999) argue that such apparent disequilibrium is actually a dynamic equilibrium. Hence, boundary spanning is critical (to the system equilibrium) as the agents (and other resources) shift/ manoeuvre activities and behaviours to maintain the equilibrium with other co-evolving systems (balancing the needs/goals of multi-stakeholders both within and external to the project TMO). Thus, Brown and Eisenhardt (1998) and Weick (1979) argue that organizations can continue to exist only if they maintain a balance between flexibility and stability (analogous to the balancing of plasticity and robustness of boundary objects). Additionally, they contend that the strategic equilibrium over time for an organization is a combination of frequent small changes made in an improvisational way (e.g. evolving use of subcontractors) that occasionally accumulate into radical strategic innovations, changing the terms of competition fundamentally (e.g. imposition/adoption of PFI).

Simon (1996) points out that any adaptive entity contains an adaptive inner environment and that complex adaptive systems are nested hierarchies which contain other complex adaptive systems. More importantly, every aspect of a complex adaptive system (agents, their schemata, the nature and strength of connections between them, and their fitness functions) can change over time, i.e. new systems may appear, old systems may become extinct, and existing ones may survive in a fundamentally new form. Hence, a complex engineering project is an adaptive entity containing an adaptive inner project environment with its own nested hierarchies of complex systems of participant organizations and an external project environment with complex stakeholder network systems. It is at the boundaries of the systems where management of agents, objects and spanning activities occur to maintain the adaptiveness and flexibility of the systems to achieve dynamic equilibrium in order to yield the desired outcome for complex engineering construction project procurement—i.e. flexibility in the process (system) enhances robustness of outcome achievement.

Boundary management is, therefore, very important for complex engineering project delivery where networks of firms deal with a myriad of task, specialization, resource and other boundaries in the execution of complex (and, often, interdependent) projects.

Project governance and control

Governance is 'The action or manner of governing ... Controlling, directing or regulating influence; control, sway, mastery' (OED, 2011). Samset *et al.* (2006) note the OECD's six principles of good governance—accountability, transparency, efficiency and effectiveness, responsiveness, forward vision, and rule of law. Turner (2006, p. 93) suggests that

> Project governance provides the structure through which the objectives of the project are set, and the means of obtaining those objectives are determined, and the means of monitoring performance are determined ... Project governance involves a set of relationships between a project's management, its sponsor, its owner, and other stakeholders.

Clearly, the essentials are determining objectives and ensuring that organizational processes and resources are employed to maximize the potential for their effective and efficient pursuit—through determining and achieving, if not surpassing, performance targets. However, much control is illusory—many persons believe that they are able to control much more than is the actual case (Kahneman and Lovallo, 1993).

The multiplicity of technologies, stakeholders, etc. indicates the very large number of boundaries on engineering construction projects and, thence, the difficulty of identifying objectives, determining their relative importance for the project, securing commitment to them, and developing and implementing appropriate structures and processes among the diverse multi-participants which have to be addressed in governance of such projects. Those boundaries, in accordance with Turner's definition, are both internal to organizations and the project, and external; their management, notably, boundary spanning, is underpinning of the relationships experienced. The formal governance provides the framework—organizational model, contractual rights, duties, procedures, etc.—while the operation of the informal system within (sometimes, in spite of) that framework provides the *de facto* governance.

Perspectives on governance of organizations and of projects has moved from command and control, to transaction costs and agency, to co-evolution and self-organizing (key components of complexity theory) (see e.g. Winch, 2001; Miller and Hobbs, 2005; Miller and Lessard, 2008; Klakegg, 2009; Ruuska *et al.*, 2011). Winch (2001) notes the importance of trust for project governance, especially under high uncertainty; in project circumstances, the level and type of trust (and perceived trustworthiness) are likely to be a function of boundary management and the boundary spanners-in-practice. Winch notes the impact of professional institutions on governance—really supplementing trust with assurances—which may be extended to the array of social institutions in which the project is embedded and to which the boundary spanners relate (see e.g. Hagen and Choe, 1998; Bachmann, 2001).

Ruuska *et al.* (2011) suggest seven key operational elements of governance of large, complex engineering construction projects—contract, organization and execution of procurement, management of networks of suppliers, risk allocation and management, work coordination and monitoring, practices and collaboration among participants, and communications. That mix of formal and informal governance elements concerns boundary management intimately, indicating the roles of boundary spanners-in-practice for project governance (the informal/social elements supplementing and reinforcing the formal elements noted in the contract documents).

Flyvbjerg (2009), from analysis of 258 major engineering construction projects (mostly infrastructure), argues that accountability, as a primary principle of governance, is achieved in the public sector through 'transparency and control' and in the private sector through 'competition and market mechanism' (p. 359). A continuing theme in Flyvbjerg's research is the advocacy of the 'outside view', notably, comprising 'reference class forecasting' (Lovallo and Kahneman, 2003; Flyvbjerg, 2006) and criticism of political and internal forecasting mechanisms which incentivize fallacious predictions of outcomes to secure authorization of projects (Flyvbjerg *et al.*, 2002). That may be attributable to project boundaries being sufficiently impermeable to isolate the project from informed external scrutiny (inadequate transparency) and so may reflect a breakdown/detriment in boundary management.

In effecting governance of projects, Turner and Keegan (2001) determine two key functional roles—broker (for external liaison) and steward (for internal management of the project). However, they note the fuzzing of roles in engineering construction where a 'project director' deals directly with the client, following establishment of contact by the marketing department, and executes oversight management of the project with a line management network of subordinates. With repeat orders and only a small number of firms able to undertake large, specialist engineering construction projects—commonly, as ologopolosts (Hobday, 1998), the functions of broker diminish (to maintaining good, or, at least, reasonable relationships—which, along with reputation, depend on performance on projects) and so, the emphasis vests in stewardship due to interdependencies and complexities of project realization activities. Thus, the role of project director becomes oriented to optimizing overall project realization performance, with responsibility for activities, and their detailed coordination, delegated down the managerial hierarchy.

Bruzelius *et al.* (2002, p. 147) assert that 'if all groups which feel concerned are included in the project development process ... at an early stage, the chances would become better that those conditions which people view as important to making a decision would be taken into account'. That stresses the external, broker role of boundary spanners to identify both the stakeholders and their requirements early, due to the important, prevailing impact of early decisions (such as selection of the procurement 'route') but, most importantly, to ensure that the performance forecasts—and, hence, expectations—are realistic.

Recent research on project governance stresses the need for 'a flexible strategic process' (Miller and Hobbs, 2005, p. 47) in which governance structure adapts/evolves in response to changes in the project environment, emergence of unforeseen events, and requirements of the different stages in project realization (Miller and Hobbs, 2005; Samset *et al.*, 2006; Ruuska *et al.*, 2011). In practice, formal systems tend to be fixed for a project's duration but the informal systems are much more flexible and do evolve. That requires the boundary managers to be adaptive to maintain the integrity, effectiveness and efficiency of both the total system and its constituents, and a formal governance regime which allows the practices of governance to evolve within the overarching regulatory framework.

Discussion—current practices and future potential

Current practices

Engineering construction projects may be caricatured as joint ventures (due to interdependencies), commonly involving many different participants in their various lifecycle phases. An important question is: 'To what extent does each participant recognize that, although their objectives are realized through their own performance on the project that performance is dependent on the performance of other participants also?' Recognition of interdependence moves participants towards cooperation and collaboration which also mitigates the consequences of boundaries. Thus, one important task of (project) management is to determine the commonalities and compatibilities of stakeholders' goals/objectives and ensure that they are articulated and communicated, preferably agreed and accepted, with a view to securing higher levels of commitment and, consequently, performance (see Nicolini, 2002; Dainty *et al.*, 2005).

Thus, management of boundaries requires awareness of own goals/objectives and of the goals/objectives of the other parties; in the cases of projects, that includes awareness of expressed/agreed objectives for the project. Usually, others' objectives but also, all too often, project objectives and the objectives of own organization are either unexpressed or expressed in such vague generalizations (common in corporate 'mission statements') that significant assumptions must be made to render them operational. Notably, assumptions are not always correct! The objectives are used to decide actions and so, behaviour and, thence, impact on performance and outcomes for stakeholders; hence, operational clarity is essential.

Levina and Vaast (2005) articulate the functional relationship between boundary spanners-in-practice and boundary objects-in-use. Boundary spanners-in-practice:

(1) 'reflect on objects from each field and reflect on their utility within the context of the new joint field' (p. 354);
(2) 'create new artifacts (or adopt existing ones) and attempt to establish their new identity within the new joint field' (p. 354);
(3) 'use various species of capital to establish the local usefulness and symbolic value of the artifacts they are promoting as boundary objects' (p. 355);
(4) use emerging boundary objects-in-practice 'to signify their position in the new joint field and the position of their field vis-à-vis others' (p. 355).

There is a small amount of emerging evidence that use of procurement routes which foster integration of designers, and of designers with constructors, leads to projects with improved project management performance (time and cost) (Constructing Excellence, 2007; Vasters *et al.*, 2010). (Note that Vasters *et al.*s' findings are tentative and that in respect of 'demonstrator projects', the outcomes may be somewhat questionable due to the likelihood of elements of 'self-fulfilling prophesies' being present.)

Engineering construction projects are labour intensive; the organizations which carry out those projects are appropriately regarded as social collectivities which draw on individual and social expertise (knowledge and skills) to produce goods and services (see Kogut and Zander, 1992). Given the multiplicity of expertise required for engineering construction projects and the diversity of organizations within which the expertise resides, there are significant differences in professional values and allegiances which are difficult to integrate, especially within TMOs and with the presence of different professional dialects (if not different languages). Thus, boundary spanners, and the boundary objects which they assist to generate and use, are vital for communication and coordination. Higher order considerations, notably, trust and commitment, operate to foster development of a common language and processes among participants, all of which are enhanced through long-term relationships, adhering to the theory of familiarity (Aldrich, 1971; Das and Teng, 1998). Unfortunately, such developments are severely restricted through the lack of continuity of employment of organizations and personnel over series of projects (programmes).

In engineering construction projects, a large array of diverse boundary objects is used—many at multiple stages and for multiple purposes (briefing documents, value management reports, contracts, drawings, specifications, product guarantees, etc.). The separation (fragmentation) of the various disciplines and organizations which use such objects is extensive and widely documented (see, above) and the interpretive variability gives rise to conflicts, disputes and claims. Whether such problems arise due to vagueness in the boundary objects themselves, the paucity of boundary spanning to foster cooperation and commitment due to goal conflicts between participants, effects of work allocation systems (which operate as zero-sum games), the level of risks which must be assumed compared with the level of returns, or combinations of those constructs is contested.

In realizations of construction projects, CAD programs are becoming increasingly extended in scope and, through 3-D and 4-D versions, as in BIM, greatly assist boundary spanning through visualization and appreciation of components, processes and their consequences—such as safety issues during construction, adaptation and disposal. Such boundary objects are also used to help maintenance provisions and processes and help to foster designers' and future occupiers' understanding of how the completed project is likely to work. Thus, those boundary objects demonstrate success as common information spaces used by project participants who, thereby, interact and coordinate their activities while maintaining their own goals (see Bartel and Garud, 2003, above).

However, in many engineering project contexts, extensive proportions of design and manufacturing are subcontracted (80% for some aircraft projects; Lawrence and Scanlan, 2007). Such diverse and widely (spatially) distributed teams, each of which contributes to a common, central virtual model, give rise to significant risk of input errors becoming incorporated and distributed to others as only (very) few persons may be empowered and have adequate knowledge to scrutinize the total model; simple errors (clashes) may be detected automatically by 'failsafe' devices but other, less obvious and, potentially, very serious errors may be very difficult to detect early.

Human/organizational perceptions of other participants, their objectives and anticipated behaviour (which depend on experiences, reputations and own disposition towards trust, competition, etc.) are likely to impact on the contents of and access to (certain) boundary objects in order to contain/constrain or to communicate/share information and knowledge. Although trust and distrust are commonly viewed as opposite ends of a single dimension, that perception may not be appropriate (Lewicki *et al.*, 1998). Given that many business relations are multi-faceted, and trust may be regarded as arising out of one or a combination of causal factors (own disposition, reputation of the other(s), and own experience of the other(s)), 'relationship partners might trust each other in certain aspects, not trust each other in other respects, and even distrust each other at times' (ibid., p. 450). The outcome suggests the contingent natures of relationships and, thence, of boundary management and its consequences. There are quite likely to be differing outcomes from combinations of boundary activities for the various in-groups and for the organizations (temporary—as TMOs/quasi firms; and permanent—firms) in which they are embedded.

Trust and power, in the context of participants' objectives, and social and legal norms and constraints, are important concerns for the development of boundary objects and how they are perceived and used. Bechky (2003b), through examination of engineering drawings, etc. as boundary objects, notes their development by engineers and managers but their use in production by operatives and others in situations of contested goals and power differentials, thereby giving rise to dissonance between intentions and actual uses leading to re-work, claims, and a control requirement (all of which are detrimental to performance). Bachmann's (2001) view that trust and power are means of social control within business relationships is revealing, especially in the light of Korczynski (2000, p. 178), who finds that for most relationships 'In situations of power imbalance there is a temptation to enforce cooperation through power rather than trust'—as is frequently the case in engineering construction projects. Those issues are important for determination of appropriate systems of project governance, both formal and informal (see Ouchi, 1979; Lewis and Roehrich, 2009).

Even within the overlay of partnering procurement to encourage cooperation between parties on construction projects (see Bresnen and Marshall, 2000a, 2000b; Bresnen, 2010), boundaries remain distinct between organizations due to differing interests and perspectives. That suggests insufficient awareness of mutual interdependencies to motivate collaboration, despite the formal contracts and the particular partnering processes adopted (partnering workshops and the production of partnering charters as contract documents). Thus, the differences are highly ingrained and Bresnen (2010, p. 625) demonstrates 'the difficulty of using designated boundary objects as mechanisms to achieve integration where practice, is highly decentralized, diffused and distributed' (Sapsed and Salter, 2004) and thus, emphasizes the importance of boundary spanners' skills in developing and fostering human relationships.

Attention to partnering and other relational considerations (e.g. relational contracting, including attention to covenantal relationships) lie along a purposive spectrum of rationale from impacting on performance to impacting on the social relationships (primarily, in the project workplace). The perspective adopted seemingly reflects (degrees of) positivism/functionalism and interpretivism/social constructivism epistemologies, in alignment with being and becoming ontologies (discussed by Winter *et al.*, 2006 *regarding projects*). Whether the goal of improving relationships is to effect improvements in project (realization) performance or to improve relationships as a social 'good', it still places onus on boundary management to foster commitment, collaboration, attachment and harmony and to prevent negative conflict, etc. Hence, projects are seen as media in which boundary management can secure greater meaning, sense of worth and achievement (self-actualization—Maslow, 1954).

Boundary management may be regarded as safeguarding self and own interests while endeavouring to overcome the boundary in order to gain from others. However, in more collaborative/altruistic climates, the endeavours to overcome the boundary are to foster collective/mutual gain through pooling and sharing of resources and outcomes ('win-win' outcomes as non-zero-sum games). In the context of international joint ventures (IJVs) those who manage across boundaries, 'boundary spanners', 'are "judges" of procedural fairness, "gatekeepers" of inflows … and "representatives" of outflows' (Luo, 2009, p. 393).

Implications for engineering construction future potential: suggested research agenda

Team boundary management is a significant contributor to team performance outcomes, including team innovation, efficiency and goal achievement (Marrone, 2010). These benefits appear to exist across team types, such as development teams, production/ service teams and action teams. That observation generates a working proposition that, by operating through the informal system, boundary management impacts on performance irrespective of the formal structuring or project organization. Analogous to safety, boundary management reduces performance-impairing hazards (of negative conflict, opportunistic behaviour, etc.) and so, its effectiveness may be assessed through metrics of effects which affect performance detrimentally (e.g. disputes, claims, accidents). Hence, boundary management is likely to contribute to project and organizational performance among stakeholders.

Therefore, it is suggested that it is neither the organizational structuring of engineering construction projects as hierarchies, markets or hybrids, nor the degree of overlapping of activities (as in several procurement practices) but good management of boundaries which yields cooperation and collaboration (internal commitment to in-group plus external commitment to 'project') and so, distinguishes the levels or performance of projects and project management which are achieved.

Thus, in educating and training engineering construction project managers (and hence, for future practice), recognizing projects as complex adaptive systems directs emphasis to raising awareness of, and sensitivity to, the emergent performance requirements and parameters of the many, diverse participants and stakeholders—due to their differing values, cultures, practices, languages, knowledge, etc. and the dynamic natures of equilibria. Such recognition is the essential basis for managing across the interfaces/boundaries to appreciate the consequences from a 'competing values' perspective of 'opportunism/self' v 'collaborative' on one dimension, with 'zero-sum consequences' v non-zero-sum consequences' on the other (see Figure 2). The behavioural dimension manifests the contribution of good boundary management, while 'differentiation'–'integration' (Lawrence and Lorsch, 1967) remains a structural complement.

Several aspects regarding boundaries and their management on engineering construction projects raise important questions for the future and, hence, for research:

(1) If firms are a repositories of technical knowledge and of capabilities, as determined by the social knowledge embedded in enduring individual relationships structured by organizing principles, how are team boundaries defined and how can team boundaries be spanned most effectively and efficiently (both within and between project TMOs and the associated permanent organizations)?
(2) How do teams allocate resources across boundary activities and do teams that focus externally achieve higher performance than teams that focus internally?
(3) Do adverse external conditions (e.g. uncertainty) necessitate a greater need for boundary spanning, and how?
(4) How do network structures assist/hinder the impact of team boundary spanning activities, internal team functioning and performance?

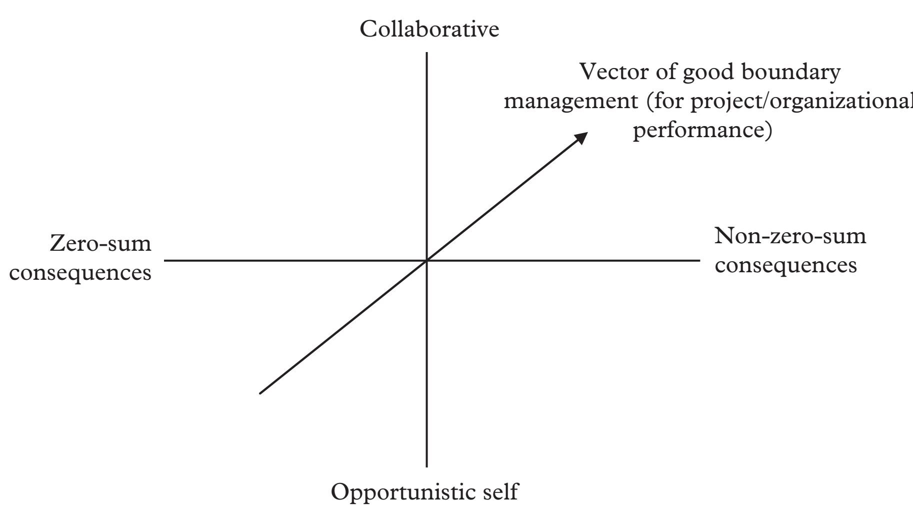

Figure 2 Competing values model of boundary management

(5) How does the use of virtual tools (e.g. autoCAD in design of engineering construction projects) affect engagement in boundary spanning activities, including the frequency, quality, effectiveness and efficiency of internal and external communications (especially if actors are widely dispersed spatially and culturally)?
(6) How are virtual tools used in the generation and use of boundary objects, and with what consequences?
(7) How does the passage of time serve to enhance/hinder bounding spanning efforts (e.g. task coordination actions), especially knowledge capturing in TMOs and in permanent organizations, and its transfer between projects (impacts on organizational learning)?
(8) How do the structural elements (size, diversity and interdependence) in the project TMO affect the boundary spanning–performance relationship?
(9) What formal project governance is (most) appropriate to be sufficiently robust for accountability while sufficiently plastic to accommodate (informal) emergence and self-organizing of complex engineering construction projects?

Conclusions

Construction is a fragmented industry—horizontally, vertically, temporally and spatially. Those dimensions of fragmentation apply to the complexity of the industry and its projects also and so the two concepts are complementary (as illustrated in Figure 1). Horizontal fragmentation is addressed through work allocation mechanisms, the most common of which remains as single stage competitive bidding with the consequent issues relating to opportunistic behaviour which have become deeply ingrained. Those consequences of horizontal fragmentation (industry) are exacerbated, if not dominated, by the effects of vertical fragmentation (project). Vertical fragmentation involves more extensive differences and, particularly through the operation of 'traditional' procurement, reinforces the zero-sum game of price competitive work allocation. Temporal fragmentation is extensive—as evidenced by the transient membership of project TMOs by both many organizations and the agents who represent them. Spatial fragmentation (local–international) operates to reinforce the other categories of fragmentation but its effects may be mitigated somewhat through alliancing and other integrative governance mechanisms and boundary spanning. Further, cultural differences, etc. remain significant—all of which operate to accentuate boundaries. Alternative procurement approaches, devised to overcome such problems (notably 'partnering') have, so far, enjoyed limited 'success' as organizational boundaries remain strong, the status quo of behaviour remains that of the 'traditional' system, and boundary spanning/management is (consequentially) constrained and limited in effects.

Engineering construction projects are nested hierarchies of complex adaptive systems involving numerous, diverse stakeholders. Thus, performance requirements and parameters are emergent and the systems co-evolve; any equilibria are dynamic. That reality is in major contrast to the common presumptions—that performance requirements are (largely) known and specified at the outset, that the process operates as per the formal governance mechanisms, and that both the process and the product realized can be strictly controlled. Incompatibility between the presumptions and reality is instrumental in generating inappropriate expectations and hence, performance dissonance (conflict, poor reputation, etc.). Therefore, it seems that managed flexibility of the realization process enhances robustness of the likely achievement of the project outcomes desired.

Engineering construction projects are replete with boundaries between project roles, organizational types, group and individual functions, communities of practice, cultures, etc. The project TMOs operate with extensive boundary infrastructures (of boundary objects) for many diverse purposes—all of which must balance the requirements of plasticity and robustness to be effective. However, engineering construction organizations require permeable boundaries to enable them to scan the environment, to obtain work and resources, and respond appropriately and speedily to changes. Thus, while formal boundaries remain fairly fixed and rigid, informal boundaries for project TMO participants are quite flexible and so facilitate organizational adaptations for performance of constituent project activities—notably, project governance.

Boundaries commonly denote demarcations of cultures, climates, knowledge, practices and resources which necessitate behavioural modifications for effective spanning and securing effective and coordinated contributions to projects through engendering adequate trust. Unfortunately, many project procurement methods and work allocation criteria remain driven by lowest (bid) price, which fosters individualist perspectives and opportunistic behaviour in the resultant zero-sum game. Such perspectives and behaviour are detrimental to trust and enhance problems of boundary spanning via bridging and bonding; they also tend to suppress recognition of mutual interdependence and, hence, commitment and collaborative behaviour by participants as own (individual) goals/objectives dominate. Such difficulties of individual organizations are enhanced in problematic environments, such as the financial 'squeezes' consequent on the 'credit crunch' of 2008.

A primary concern of boundary spanning is to nurture cooperation, collaboration and commitment through sensitivity to the diverse natures and interests of the participants and so to foster identification, communication, acceptance and pursuit of common goals (see also Nicolini, 2002; Dainty, *et al.*, 2005). That is facilitated by boundary objects which are representations of portions of knowledge drawn from one or more communities of practice (in-groups with stocks of particular knowledge and practice). Thus, the role of boundary spanners concerns securing useful boundary objects and establishing easily intelligible and usable flows across the boundaries.

Complementarily, the presence and use of suitable boundary objects promotes interactions and coordination without the necessity of shared goals/objectives. However, it is important that the boundary objects are sufficiently plastic while also being sufficiently robust; achieving a suitable balance is notoriously difficult. As boundary objects may operate to accommodate pursuit of differing goals between groups, they are important not only in the context of the organizations (groups) which constitute engineering project TMOs but also within the permanent organizations (departments, business units, etc.) and between those organizations and their shareholders—particularly regarding acceptable corporate performance as managers pursue growth while owners seek profitability (Baumol, 1959).

Thus, the management of boundaries, through boundary spanning-in-practice and boundary objects-in-use, offers a means for improving engineering construction project processes through achieving greater integration by recognition of mutual interdependencies while preserving independence. However, the difficulties relating to communications and acceptance across boundaries of different communities of practice/knowledge must also address and overcome the self-interest orientation of those communities and supplant it with appreciation and acceptance of mutual interdependence. That requires a gamut of changes—behaviour, climate and culture—requiring effort and reinforcement over the long term to be effective.

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