The analysis of information flow interdependencies within projects

Abstract

Information flow exchange within highly distributed, co-located, self-organizing and networked projects is critical for successful planning, and ultimately, for successful infrastructure project delivery. While conventional project scheduling methods are still widely used as project support tools, most lack capacity for harnessing and exploiting both direct and indirect forms of information flow interdependency between activities in these project types. The present study sets out to develop and present a practical method for modelling and analysing information flow interdependencies in infrastructure projects. We propose and apply a five-stage approach, using an integrated form of Network Analysis augmented with *fuzzy* Cross-impact Matrix Multiplication Analysis. The findings classify project activities based on their dependency levels with other directly and indirectly related project activities. The novel contribution to project management practice is that key information flow interdependencies can thus be identified and then more effectively harnessed due to an enhanced ability to interpret the information with a clearer understanding of originating communication context.

KEYWORDS: Fuzzy, MICMAC, Information flow, Interdependence, Project activities

1. Introduction

1.1 Setting the scene

The use of highly distributed, multi-located, self-organizing and networked projects to deliver strategic operational requirements is increasingly becoming popular and prevalent in today's

VUCA (volatile, uncertain, complex and ambiguous) business environment. Using highly distributed, multi-located, self-organizing and networked project teams, allows for organisations to not only be able to unpack their value-based activities, but also execute and implement them in a manner that is both effective and efficient (Mishra and Sinha 2016). Driven by a number of factors including technology, there is an increasing pressure on project managers to deliver these types of projects in 'real-time' with minimal delays. In effect, the current realities of today's business environment has put considerable pressure on organisations to dispense with traditionally bureaucratic and hierarchical structures and explore newer means of project organizing that are not only organic and flexible, but also boundaryless, self-organizing and virtual (Palmer et al. 2007; Annosi and Brunetta 2017; Smith et al. 2017; Chipulu et al. 2019). Projects teams that are highly distributed, multi-located, self-organized and networked are generally characterised as exhibiting geographically dispersal (Sarker et al. 2011). Such dispersal may often span not only organisational but also national boundaries (Van Ryssen and Godar 2000; Caldwell et al. 2008; Webster and Wong 2008). This entails a commonplace need for project teams that are "*…temporary, culturally diverse, geographically dispersed, and electronically communicating work group[s]*" (Jarvenpaa and Leidner 1999; p. 792).

As entities utilised in the delivery of the strategic objectives of organisations, infrastructure projects are increasingly being characterised as temporally bounded (Söderlund 2013), inherently ephemeral (Söderlund 2013; Tryggestad et al. 2013), amorphous (Scott-Young and Samson 2009) and self-organizing (Manning 2017). Taken together, these factors allow for more flexible, non-routine and disruptive forms of management practice. For example, practitioners are increasingly rotated in and out of projects (Riis and Pedersen 2003), in planned ways that bring about very limited or no interruption to the project (Scott Young and Samson 2009). This purported flexibility associated with newer ways of project organizing requires examination, however, within the context of appreciating that infrastructure project delivery remain inherently complex endeavours, with this complexity extending beyond design and delivery (Khan et al. 2016), to also encompass eventual transfer to operations phases (Al-Mazrouie et al. 2020)

Looking temporally at complex infrastructure projects with sequences of design, delivery and implementation in mind, such projects can be characterised throughout their durations by high-level uncertainties that are both internally and externally driven (Al-Mazrouie et al. 2020). Furthermore and perhaps of more particular interest to this study is that such projects can be characterised, within each phase, by high levels of both vertical and horizontal fragmentation (Fellows and Liu 2012; Alashwal and Fong 2015; Khan et al. 2016), owing to heterogeneity and flux of internal and external stakeholder involvements (Chipulu et al. 2019). Many of these stakeholders will maintain very diverse interests, perspectives, assumptions and priorities, which may also change over time (Chipulu et al. 2014, 2016; Ojiako and Chipulu 2014; Ojiako et al. 2015a, b). Put together, then, infrastructure project uncertainty and fragmentation, especially when analysed dynamically rather than statically, can be associated with various consequences such as sub-optimal resource sharing. And for present purposes, here we are particularly concerned with not just information, but also its managed flows, as forms of resource that can become of critical importance, especially under these combined circumstances of uncertainty, fragmentation and continual flux.

More generally speaking, resource sharing problems (including those of information exchange and use) have driven increased use of Project portfolio management (PPM) (see for example, Martinsuo 2013; Kopmann et al. 2017). It was therefore decided that in the present paper we would look to PPM theory and practice for insights on how complex infrastructure project can better deal with information and its management (which organises information within ‘flows’, as we discuss next) as forms of resource. For the present research to be focussed within manageable limits, a decision was taken to restrict attention to resource issues that relate to identifying new and emerging information flows, as well as to harnessing existing ones – which, in effect, situated matters of intelligence gathering and other forms of environmental scanning as external context for our analyses, findings and recommendations.

1.2 Information flows

A substantial literature has captured the rise of *temporary* (Bakker et al. 2016; Prado and Sapsed 2016; Stjerne and Svejenova 2016; Tukiainen and Granqvist 2016; van Marrewijk et al. 2016; Sydow and Braun 2018), *distributed* (Bourgault et al. 2008; Bardhan et al. 2013; Mishra and Sinha 2016; Xia et al. 2016; Olaniran 2017), *self-organizing* (Hoda and Murugesan 2016; Pryke et al. 2018) and *virtual* (Sarker et al. 2011; Thomas and Bostrom 2010; Olaisen and Revang 2017) organizing principles, for both organisations and projects. All of these principles are applicable to information management in particular. Nonetheless, despite the availability of various practical insights from these literatures, as projects become more complex, it remains inevitable that managing effective and efficient information flows will inevitably become more challenging (Caldwell et al. 2008; Khan et al. 2016).

Within the general context of targeted and systematic flows of information being critical to the success of highly distributed, multi-located and networked projects, one salient consideration is that these may play a sometimes strategic roles within infrastructure projects by providing a critical means of translating knowledge required for project learning (Kyriakopoulos and De Ruyter 2004). This is not least because information flow interdependencies invite critical management practice where both information itself and its management sources become scrutinised from multiple managerial or broader stakeholder perspectives across projects. The common purpose underlying such scrutiny can be framed in terms of optimally capturing, articulating, storing or retrieving project-related information, and, furthermore, of managing all associated project processes (Durugbo et al. 2011, 2013, 2014; Durugbo 2015) from which information flows emerge and are sustained. One basic premise of information flow (which is either in electronic, written or verbal form – see Yazici 2002), is that it can only be manifest where two or more entities (for example, individuals or project teams or units) are related or connected (Correa da Silva and Agusti-Cullell 2008). Therefore, the more complex and fluid the project structures and relations are, the more information sharing processes there are likely to be, upon which critical management attention can focus.

1.3 Activity and/or task interdependence

Project activity relationships, which are likely to be considerable with further reference to multiple processes operating, are likely to take shape in different ways, depending upon whether the project activities that interface through these relationships are: (i) independent, (ii) dependent or (iii) interdependent of one another (Yassine and Braha, 2003). It has also been contended that the third of these possibilities will tend to predominate; that is, projects generally involve highly interrelated and therefore, interdependent activities where multiple associated processes feed or feed off one another within the general informational milieu (Maheswari et al. 2006). This general likelihood begs many further questions about the relationships between the various management processes at issue, each of which may have its own discrete and hermetically sealed logic, and developmental history. Given that project activity and/or task interdependence is well recognised within academic literature as a major contingent factor for project success (see for example, Pinto and Slevin 1987; Morris 1988; Hoegl and Weinkauf 2005; Sosa 2014; Schoenherr et al. 2017; Zhao et al. 2020), it becomes reasonable to posit that critical and collaborative management practice, focussed on underlying processes and seeking more effective and efficient management of project information flows generated through these processes, will tend to be positively correlated to project success.

A further complexifying factor when examining information flow interdependency is the artificiality of the project boundary. That is, most organisations do not commission projects as stand-alone entities (Martinsuo and Lehtonen 2007; Görög 2011; Eriksson 2013); rather, most projects are commissioned as part of a wider portfolio (group) of interdependent projects (Archer and Ghasemzadeh 1999). Looking from this broader PPM perspective, it becomes clear that information flows and their underlying processes may not be fully grasped without appreciating also that they may frequently span multiple projects across time and space.

A further complexifying factor is that contributing underlying processes can be theorised on various scales. That is, most projects are never characterised by the implementation of single, sequential activities and/or tasks; instead, they are typically sub-divided and broken down into smaller '*activities*' and/or '*tasks*' or '*work packages*' which each raise their own process issues at relatively micro level where information and its management offer immediate practical value. In this study, for brevity, we will use the term '*activities and/or tasks*' to speak to the scale of management process with which we are chiefly concerned, which, as we have indicated, we situate on the micro level, close to the epistemic needs of project managers in their workaday lives. Given that project 'activities' and/or 'tasks' are typically assigned to different actors who manage them before the 'final' project is re-integrated into a whole for delivery to the client, this focus is arguably best suited to capturing project complexity prior to the operational phases of projects, which we earlier specified would be included within our research scope. Nonetheless, it was felt that this focus would also remain pertinent to a significant extent for all project phases. We regard ‘activities’ and ‘tasks’ as, in effect, ubiquitous across project phases, while even being pertinent to information exchange and learning that transcends project boundaries.

One further challenge for analysing information flows in infrastructure projects’ is that they also raise risk and opportunity issues that transcend their originating information management contexts. For example, when properly managed, information flow resources become stakeholder trust building opportunities (Sarker et al. 2011). Or, used more dysfunctionally so as to constitute internal risk, information flows become technologies of power that can reinforce exploitative behaviours among team members (Brown et al. 2004), or perhaps intra-project boundaries.

1.4 Our study aim

In light of the above context, this study sets out to develop and present a practical approach for analysing direct or indirect information flow interdependencies within infrastructure projects. The proposed approach involves five steps; (i) identification of pertinent activities; (ii) mapping of their interdependencies; (iii) measuring the levels of associated information interdependencies; (iv) network visualisation, and (v) category analysis of information flow interdependencies, aimed at practitioner use. Modelling is a popular method of decision support (Moe and Kaivo-oja, 2018). It is also one of the most widely used analytical methods in infrastructure project management (Flood and Issa, 2009). Modelling has been employed to enhance efficiency of both project scheduling and articulation of project activity interdependencies, by drawing pertinent explanatory categories to light (Amigo et al. 2013).

The approach which we propose for articulating the pattern of information flow exchange in infrastructure projects is the Design Structure Matrix (‘DSM’). Developed by Steward (1981), DSM allows for simple visual representations of structural interrelationships, expressed as square matrixes. This is widely used and remains popular in project management. Recent applications in project settings include studies by Maheswari et al. (2006), Danilovic and Browning (2007), Shi and Blomquist (2012), Browning (2016) and Piccirillo et al. (2018).

Our proposed study approach is largely framed and aligned to the method adopted by Arantes and Ferreira (2020). Our data is based on the outline from the design stage of a major building development project undertaken in the United Arab Emirates (UAE). Our rationale for focusing on the design stage, for mapping purposes, is that it is a core part of the ‘front end’ of projects. Numerous studies have pointed out that the ‘front end’ of projects is typically most critical because it is the stage where poor management is most likely to lead to project failure (Morris 2011; Edkins et al. 2013; Bloomfield et al. 2019; Williams et al. 2019). Not surprisingly, design management is regarded to be critical to the success of infrastructure projects (see Wang et al. 2015).

We recognise that, as Cox and Thompson (1997) observe, infrastructure project delivery is “*…inherently site-specific”* (p. 128). However, Dubois and Gadde (2002) point out that the complex nature of interdependencies between activities on most infrastructure projects tends to favour the use of standardised plans, which may be adjusted to local conditions. Bearing the benefits of standardisation in mind, although our data derive from the building construction industry situated within the United Arab Emirates (UAE), it was anticipated that findings are likely to be more broadly generalizable, especially for more complex projects. Here it is also important to consider that project scheduling problems continue to be a reality for complex projects in general

(Browning and Yassine 2010; Hartmann and Briskorn 2010; Wang et al. 2014; Moradi and Shadrokh 2019; Pellerin and Perrier 2019). Furthermore, a number of proposed methods for project scheduling lack practicality (Herroelen 2005). The present research was designed in the hope that findings may contribute to this literature by indicating how projects might be better scheduled so as to optimise creation and exploitation of complex information flows.

2. Project activities, interdependencies and scheduling

2.1 Theory

Pinto and Prescott (1990) suggest two distinct groups of critical success factors in projects: (i) those focused on initial project planning and (ii) those focused on project operations. A key function within project management is activity and/or task planning and control (Pellerin and Perrier 2019). In fact, Pinto and Prescott (1990) opined that a lack of planning is *the* most critical driver for project failure. Undertaking activity and/or task planning and control generally entails a number of project-related managerial actions, including activity and/or task scheduling.

The theoretical development of our understanding of ‘*activities and/or tasks interdependence’* can be founded within elements of work undertaken by Jeff Pfeffer (1972, 1987, 2003, 2005). Within a project context, reference to ‘*activities and/or tasks interdependence’* implies drawing from Schoenherr et al. (2017), to “…*the extent to which the successful completion of an individual project activity and/or task is dependent on another project activity and/or task*”. The implication of this is that successful completion of a project activity may very often hinge upon its interdependences with perhaps several other activities, each of which can be further analysed for its own interdependencies. Pfeffer’s work (1972, 1987, 2003, 2005) has been particularly focused on articulating exchange relationships as the foundation for assessing interorganizational power relationships (especially where exchanges reflect power relationships. Recognising this point, the present study considers three primary and closely interrelated elements in what became Pfeffer's Resource Dependence Theory (RDT) as follows. These are first, the '*social'* context of interrelationships, which in projects will entail our appreciation that the management of project activities and/or tasks will entail social interactions. Second is '*strategy'*, which, contextualised within projects, posits the possibility of enhancing the interest of specific project activities and/or tasks through prioritization. Third is the relationship between '*power'* and '*interdependence'*. Here we note that activity '*x'* is dependent upon activity '*y'* to the degree that '*x'* maintains power over '*y'*. If activity '*x'* and activity '*y'* maintain power over one another, then they are deemed to have an '*interdependence'*. However, it may not always be the case that two activities maintain a balanced power over each other. When an imbalance of power exists for example, between activity '*x'* and activity '*y'*, the activity with a lesser power becomes dependent on and a liability to the activity with more power. Generally, we expect that if activity '*x'* has more relative power over activity '*y'*, in the scheduling of project activities, activity '*x'* will be given more priority (for example, in terms of allocation of resources or granting of access to available information) over activity '*y'*, suggesting a relationship between '*power'* and '*value'* which can be construed as the "*…utility [and] benefit elements of resources offered*" (Ramsay 2005; p. 550 and p.560)).

What this means is that low levels of '*activities and/or tasks interdependence'* may be ideal from the perspective of multiple highly distributed, co-located, self-organizing and networked projects. With low levels of interdependence, risks associated with any demand for high levels of project co-ordination (and integration) are greatly reduced (Gorton and Motwani 1996). Conversely, drawing from Mishra and Sinha (2016), we expect a high level of project coordination to be required in conditions where *activities and/or tasks interdependence* are poorly defined and a lower level of project co-ordination to be required where *activities and/or tasks interdependence* are clearly defined.

2.2 Evolution of scheduling tools

To support project planning and more specifically, activity and/or task scheduling, over the last few years, numerous conventional project management scheduling tools such as the Critical Path Method ('CPM') (Kelley 1961; Kohler, 1975) and the Program Evaluation and Review Technique ('PERT') (Roman 1962) have become available for practitioners (Morris 1988; Demeulemeester and Herroelen 2002; Herroelen 2005; Hoegl and Weinkauf 2005; Demeulemeester and Herroelen 2007; Ballestin and Leus 2009; Pellerin and Perrier 2019; Zhao et al. 2020). However, while these tools are able to handle sequential and parallel project activities, they do not have the capability to do so as relates with the interdependencies between different activities and/or tasks or in fact, different information flows (Maheswari et al. 2006). This makes the use of these tools unsuitable when seeking to articulate the real nature of these interdependencies (Pellerin and Perrier 2019). More specifically for example, the CPM is unable to effectively cater for activities that are undertaken in parallel or sequentially (Oloufa et al. 2004). The limitations of CPM and PERT have made demands for scheduling tool that are more functional sophisticated. This has led to an evolution from the deterministic origins of planning and scheduling tools to an increasingly fuzzy functionality capable of catering for the uncertainties associated with infrastructure projects. In many instances, these newer tools are developed to be heavily dependent on technology in order to improve their effectiveness and efficiency. Pellerin and Perrier (2019) have undertaken a very comprehensive review of project planning and control methods. Thus, for brevity, we have not undertaken such a review in this paper. One particular point of interest which emerges from their study is that they observe that increasingly, the literature appears focused on the development of non-deterministic project planning tools that are capable of aiding project planning where there is incomplete and vague information.

2.3 Activity and/or task scheduling

To mitigate against project escalations and project delays, Malone and Crowston (1994) emphasised the need of "*…managing dependencies between activities performed*" (Malone and Crowston 1994; p. 90). There are generally three types of '*interdependencies'* manifest between different project activities and/or tasks; namely '*flow'* '*fit'* and '*sharing'* (Malone and Crowston 1994). The first '*flow'* is utilised to describe an interdependence which arises when one project activity and/or task produces a resource which is then utilised by the next sequentially occurring activity and/or task. Second is '*fit'* which is utilised to describe the collective production of a single resource by multiple activities and/or tasks. Third and lastly is '*sharing'* which describes the use of one resource by multiple activities and/or tasks.

As the level (intensity) of project activity and/or task interdependence can vary (Adler 1995; Sosa 2008, 2014), the scheduling of project activities allows for overlap (Dehghan et al. 2015). This means that, under specific conditions, activities which are '*downstream'* can commence before the end of '*upstream'* activities. This overlap can occur either after a specific duration of the '*downstream'* activity or at the point a percentage of the work associated with it has been undertaken. This is referred to as '*lags'* (see Meier et al. 2015). However, research have shown that the incorrect use of '*lags'* in articulating the relationship between project activities can generate a number of scheduling challenges, including increased modelling complexity (Francis and Miresco 2006). To address these challenges, *Concurrent engineering* (CE) has attracted the interest of scholars (see Rolstad 1993; de la Garza et al. 1994; Swink 1998; Koufteros et al. 2001; Anumba et al. 2002; Yassine and Braha 2003).

What makes the management of project activity and/or task interdependence particularly challenging is the formal and informal and direct and indirect intricacies involved in information flow between the different project team members (and stakeholders) involved in managing these different activities and/or tasks. The implication of the variation in the level (intensity) of project activity and/or task interdependence is that the extent of management for various interdependences may differ.

2.4 Sequencing and scheduling

To manage project activities and/or task interdependencies, the general approach has been to undertake explicit '*sequencing'* (Malone and Crowston 1994; Herroelen 2005) and '*scheduling'* (Demeulemeester and Herroelen 2002, 2007; Herroelen 2005; Schatteman et al. 2008; Browning and Yassine 2010; Hartmann and Briskorn 2010; Yassine et al. 2017). Scheduling refers to "…*the process used to determine the overall project duration and when activities and events are planned to happen. This includes identification of activities and their logical dependencies, and estimation of activity durations, taking into account requirements and availability of resources*" (APM 2006; p. 36). It is a "…*complex process involving many types of resources and activities that require to be optimised*" (Moradi and Shadrokh 2019; p. 3139). Scheduling helps project stakeholders not only set out, but also manage, their varying expectations about the project (Chipulu et al. 2019). Schedules render project stakeholders more able to estimate, document, track and report upon their expectations. They also constitute an important part of project planning (Pellerin and Perrier 2019), and generally involve some ordering, allocating, controlling and monitoring of activities and/or tasks in a project. As the main emphasis within scheduling is on the network of activity and/or task timescales, trade-offs and sequence orderings, to schedule project activities and/or tasks, the norm is usually to explore precedence (in effect, by thinking causally about activity prerequisites). Scheduling will also involve exploring constraints on resources, especially where such resources need to be shared by different activities and/or tasks (Herroelen 2005). Scheduling can be undertaken either proactively or reactively when pertinent information comes to light and will inevitably tend to combine elements of both (Sabeghi et al. 2015).

The key attributes of an activity that matter for task scheduling purposes include time and cost (Herroelen 2005; Demeulemeester and Herroelen 2007). Their variabilities will tend to necessitate some reactive scheduling. Furthermore, often during scheduling there is a requirement for a specific project activity and/or task to be completed by a set deadline on the condition that penalty costs are applied for missed targets. For the manager responsible for the delivery of specific activities and/or tasks, it therefore appears that the completion of a specific project activity and/or task will be for its completion prior to or within its scheduled deadlines (Pellerin and Perrier 2019). In project management practice, specific dates for project activity and/or task completion will be set prior to or during project commencement with the expectation that the responsible project or work package managers will liaise with their teams to ensure that agreed deadlines are met. Such schedule management within teams requires further recognition, however, that it would be very poor risk management to assume that plans for meeting deadlines cannot be thrown awry by aleatory uncertainty. Hence scheduling requires sensitivity to the uncertainties that surround an activity, so that appropriate allowances can be made for some reactive element.

2.5 Scheduling in infrastructure projects

Project scheduling primarily involves not only integrating information emanating from interdependent project activities and/or tasks, but also managing the associated flow of information in to ensure optimal co-ordination and use. A core attribute of infrastructure projects is that they entail multiple, highly distributed, co-located, self-organizing and networked project activities and/or tasks. One way to tackle the challenge of harnessing such highly distributed information is through 'risk intelligence work' (Marshall & Ceylan, 2020) which draws project managers together to consider the interfacing of various information related processes such as those pertaining to risk and uncertainty management, marketing intelligence, competitive intelligence, and change and issue management. Such risk intelligence work can be proactively scheduled within formal information exchange hubs, or it can be more reactively scheduled within informal huddles that form more spontaneously, and operate more at 'clockspeed', to address particular issues that have arisen (Lopez de la Cruz et al. 2020). Nonetheless, the gulf between advanced practice and common practice remains wide. We remain mindful of how susceptible infrastructure projects are to information management failure, due to a combination of poor quality and volume of information exchange (Parraguez et al. 2015). As we have explained, this is partly attributable to the enormous challenge whereby scheduling and planning require a full understanding of the degree of complexity of the interrelationships between various project activities and/or project tasks (Chan et al. 2019). Moreover, the project scheduling challenge has been represented as largely dependent on four factors: (i) whether specific project activities can actually be overlapped, (ii) the degree of such overlap (Meier et al. 2015), and (iii) the nature of the activity (Maheswari et al. 2006) and the associated susceptibility of its sequencing to variability (Lindhard et al. 2019) and (iv) whether activity durations can be robustly predicted (Chan et al. 2019). What further complicates project scheduling and planning is that despite what may be purported in the academic literature (see for example, Cummings et al. 2009), the true nature of *activities and/or tasks interdependence* is evolutionary. This basically means that the nature of *activities and/or tasks interdependence* often evolve with new interdependencies emerging and old interdependencies disappearing as time goes by (Sosa et al. 2004). Hence, it is plausible that those responsible for project planning may not have a full grasp of the nature of *activities and/or tasks interdependence* until much later during the project lifecycle (Ethiraj and Levinthal 2004). Nonetheless, and recognising as a key attribute of the management of information flows, the aspiration to ensure that the effectiveness and efficiency of the project is enhanced through routinization (see Huo et al. 2016), it can be argued that co-ordination of information flows through formal information hubs, rather than taking a more information huddle approach, is preferable where possible.

2.6 Information flows

Drawing on Marchand et al. (2000), when we discuss the effective management of information flows in a project management context, we imply reference to the project team's ability to exchange information which remains accurate and is kept free from manipulation and bias. This might involve, for example, giving careful thought to reliability and credibility issues, or perhaps critical reflection on the relative concreteness or abstractness of the information (Marshall and Ceylan, 2020). Understanding information flows from this standpoint, emphasising the need to assess and preserve the integrity of the information itself, sets the information management challenge in a new light and points towards several benefits. For example, information that is managed in this aspect, can offer a reliably impartial and shared understanding of project activities and/or tasks (Chipulu et al. 2019). Without actively striving towards such an understanding, it is likely that the project will become more susceptible to conflicts of misunderstanding.

The management of information flows also involves giving regard to information availability issues, for example within crisis and other non-routine management contexts of urgent need. Being highly distributed, co-located, self-organizing and networked, it follows that infrastructure projects require information to be synchronously available to numerous project stakeholders within such contexts (Caldwell et al. 2008). A *complexifying* factor is, of course, that project teams are temporal, ephemeral and ever evolving (Scott-Young and Samson 2008, 2009; Parraguez et al. 2015). Furthermore, managing these information flows so as to optimise availability can be valued in terms of its resource savings. Evidence suggests that in both organizations (Caldwell et al. 2008) and in project environments (Tribelsky and Sacks 2010, 2011; Xu and Luo 2014), staff, employees and project stakeholders do expend substantial time not only searching for information, but also seeking to piece together various information sources in order to facilitate effective decision-making. Moreover, it is likely that due to the extent and intricacy of activity interdependence in infrastructure projects, some combination of paucity of information and a lack of understanding of its flow interdependencies, will tend to exacerbate undesirable project escalations under non-routine management circumstances (Herroelen 2005), thus causing project delays (Sosa 2014; Schoenherr et al. 2017; Zhao et al. 2020) and ultimately, project failure. These same informational weaknesses may thereafter undermine the efforts of the project sponsor or other related parties to conduct performance analysis or the forensic analysis of the possible project failure factors that were at play.

3. Project network analysis

3.1 The Design Structure Matrix (DSM)

One of the main attributes of a Design Structure Matrix (DSM) is that, as a square matrix, it uses bi-dimensional grids to display and to analyse bi-directional interdependencies between pairs of project activities (Helo 2006). Diagonal cells can be used to characterize the project activities while off-diagonal cells can signify interdependencies. This visual tool has numerous similar uses, such as for understanding how altering the outputs of an activity will impact upon other activities, or for configuration control and change notification (Browning 2016). Over the years, DSM has also been complemented with functionality for analysing: (i) minimisation total feedback values (Lin et al. 2012, 2015), (ii) process modularity of activities' subgroupings (Gomes and Dahab 2010), (iii) sub-networks (Micaelli and Bonjour 2011), (iv) information flow design iterations (Yin et al. 2018), and (v) measurement properties of information flow required to identify critical project activities (Luh et al. 2009; Lin et al. 2012). Another advantage of DSM is that it allows for activity repetitions of prior completed tasks (Nelson et al. 2016). It also offers simple and concise representations that render complex problems amenable to practical management solutions

Browning (2016) has pointed out, however, that there are several limitations. For example, DSM is blind to individual activity locations within project networks (Laslo 2010). Furthermore, considerable effort is required for judging the natures and extents of information dependencies. Recognising limitations, our study proposes a tailored approach focussed on suitability for capturing and analysing information flow interdependencies between project activities. This approach will be characterised by its incorporation of *Network analysis* with *fuzzy Cross-impact matrix multiplication analysis* (Duperrin and Godet 1973). We postulate that such an approach will enable project managers to develop a comprehensive view of interdependencies between project activities and/or tasks, which should offer practical use value for activity scheduling in particular. Furthermore, by incorporating a fuzzy element (Zadeh 1999), this approach addresses limitations with prior *DSM* network analysis models (Collins et al. 2009). Notably, the incorporation of fuzzy elements into project management models is a recognised part of project management practice (Padalkar and Gopinath 2016). In particular, it enables development of project management decision tools suitable for commonplace circumstances where there is limited information available to support optimised decision making (Zammori et al. 2009). Embedded in our proposed *Integrated Network-fuzzy Cross-impact matrix multiplication analysis* (MICMAC) approach are new categorization and classification systems than can be used to identify critical project activities based on the extent of direct and indirect information interdependencies between these activities. Next we explore the nature of these networks further.

3.2 Network analysis modelling

To enable consideration of (i): direct and indirect dependency levels between project activities and (ii) iterative and interactive interdependencies between different project activities, network analysis (Wasserman and Faust 1997) provides an appropriate toolset. It is sometimes considered is particularly useful for analysing complex activity relationships within projects (Lee et al. 2017; Wang et al. 2018). In summary, complex relationships can be better understood because network analysis allows for the structure of a network to be metricised at both network level network and also for contributing nodes.

Among the most applicable metrics for analysing interrelationships between project activities are '*network density*' and '*degree-centrality'* metrics (Lee et al. 2017). Here, '*network density*' measures relative quantity of ties amongst nodes (activities) within the network. This is calculated as a proportion of the sum of interrelationships that exist between these nodes (activities) equated against the compounded number of likely ties that will exist if each node (activity) was interrelated with every other node (activity) (Wasserman and Faust 1997). In the context of our study, this metric can be employed to serve as a means of articulating the levels of network complexity due to the high degree of interrelations between various project activities. What this implies is that if the calculated '*network density*' is determined as high, then specific steps should be taken to minimize the level of the network density, thus minimising to a manageable level, project complexity. Nevertheless, '*network density*' is unable to show which node (activity) or nodes (activities) are substantially dependent on others or which are *more* substantially dependent on others (in effect, '*network density*' is unable to articulate dependence levels). To make such a determination, the utilisation of a *'degree-centrality'* metric is proposed.

In order to establish the level of importance and/or also to classify actors on the basis of direct relationships that exist with other network actors, network analysis literature suggests the use of '*degree-centrality'* metrics (Wasserman and Faust 1997; Lee et al. 2017). Here, '*degree-centrality'* is construed as the quantity of direct relationships for any node. For a directed network, we measure '*degree-centrality'* by taking into consideration two separate metrics. These are termed '*in-degree centrality'* and '*out-degree centrality'.* Here, '*in-degree centrality'* means the quantity (in numerical terms) of ties that are directly *in*bound to a specific node (activity). Conversely, '*out-degree centrality'* means the quantity (also in numerical terms) of ties that are directly *out*bound from a specific node (activity). In a network that is un-*dichotomised*, the quantity (in numerical terms) of relationships in both metrics (that is termed '*in-degree centrality'* and '*out-degree centrality'*) is generally substituted with the summated weights allocated to the relationships.

From what we know so far, most early applications of network analysis looking into similar relationships between nodes (activities) took into consideration either binary or weighted relationships. However, there has been recent interest in using a fuzzy approach to network analysis to deal with inexact, imprecise and ambiguous relationships among nodes (activities) in project networks (see Chu et al. 2016).

3.3 Integrating DSM with Network analysis modelling (and its limitations)

In Collins et al.'s (2009) study, DSM was integrated with network analysis to identify critical activities based on their relational roles. However, a major limitation of Collins et al.'s (2009) model was in its use of binary relations (0 or 1) to denote activities relationships. Luh et al. (2009) overcame this limitation by using fuzzy DSM for information flow modelling of project activities. Based on the information obtained via Luh et al.'s (2009) fuzzy DSM model, two metrics were used to identify the significance of the role of each project activity. The first metric, referred to as (S+R), appears to sum the values for '*in-degree centrality*' and '*out-degree centrality*'. Their further metric, referred to as (*S-R*), appears to be a subtraction of the value of '*in-degree centrality*' from that of '*out-degree centrality*'.

Drawing from Luh et al. (2009), an activity with a high value of (S+R) means the activity requires substantial information to be sent to and received from directly linked activities. On the other hand, activities with high (*S-R*) values will have a greater ability to support these other activities. Conversely, any activity that scores high on (*S+R*) or (*S-R*) is considered important and requiring managerial attention. However, one limitation of this approach is that, arguably, a high value of (*S+R*) could be obtained if the amount of information transmitted is very low and the amount of information received is very high. Conversely, an activity with such a characteristic *could* erroneously be considered unimportant. Despite the noted contributions of Collins et al. (2008) and Luh et al. (2009) to the greater understanding of project activity interdependencies, both studies share a common limitation; neither of them takes into consideration multi-level activity interdependencies. In effect, in the studies by Collins et al. (2009) and Luh et al. (2009), only first-order interdependencies were considered which we believe are insufficient to appropriately articulate multi-level information flow interdependencies between project activities. Thus, to be able to articulate such multi-level interdependencies, we opted to use *Cross-impact matrix multiplication analysis* (MICMAC).

3.4 Cross-impact matrix multiplication analysis

MICMAC (*Matrice d'impacts croisés et multiplication appliquées à un classement*) is a cross-impact multiplication matrix method of analysis developed by French scholars Duperrin and Godet (1973). The focus of MICMAC analysis is the exploration of the drivers, links and dependent factors within project activities. We employ MICMAC to undertake an analysis of the '*Driving power'* and also the '*Dependence power'* of project activities by considering both their direct and indirect impacts. Generally, there are four categories of classifications that have been allocated to these activities:

(i) Activities which are '*autonomous'*. These activities are characterised as having a '*Driving power'* and also a '*Dependence power'* which are both weak.

(ii) Activities which are '*dependent'*. These activities are characterised as having a '*Driving power'* which is weak, but a '*Dependence power'* which is strong.

(iii) Activities which are construed as '*linkages'*. These activities will have a '*Driving power'* and also a '*Dependence power'* which are both strong.

(iv) Activities which are '*independent'*. These activities will have a '*Driving power'* which is strong, but a '*Dependence power'* which is weak.

On reviewing these studies, we observed that one major challenge with the classic MICMAC is that it caters for only binary relationships (Dubey and Ali 2014). This limitation has led to the development of a *fuzzy* version which is based on earlier *Fuzzy* theory developed by Zadeh (1965, 1999). The crux of this contribution is its use of mathematical methods to articulate and flexibly represent concepts that are not easily defined. The main benefit is that under this *fuzzy* version, a decision maker is able to address problems without the need to be constrained to binary choices of either 0 or 1.

To enhance functionality, the *Fuzzy*-MICMAC model is commonly integrated with Interpretive Structural Modelling (ISM) (see Dubey and Ali (2014), Sindhu et al. (2016) and Mishra et al. (2017)). Interpretive Structural Modelling ('ISM') is a popular complex system analytical tool for transforming poorly articulated and unclear mental models for systems, into visible, organised and well-defined schemas that can be used in different settings (Mandal and Deshmukh 1994). In its most basic form, ISM breaks down complex systems into constituent parts so that models can be built (Malone 1975; Govindan et al. 2010). Using ISM to analyse relationships between information system project failure factors, Hughes et al. (2016) were able to gain insight into high dependencies between selected failure factors. Similarly, Kumar et al. (2016) drew on this approach to develop a hierarchical model of barriers to successful implementation of green lean six sigma (GLSPD). Summing up, then, there is considerable evidence supporting the use of MICMAC analysis and, additionally, the use of integrated ISM- *Fuzzy*-MICMAC model in project management scholarship. Very recent studies by Bredillet et al. (2018) and Bashir et al. (2020) highlight that such use persists within the literature.

4. The study

To apply the proposed Network Analysis *fuzzy* MICMAC approach, we employ the following steps: (i) identification of activities; (ii) mapping of interdependencies; (iii) measuring the level of information interdependencies; (iv) network visualisation, and (v) analysis of information flow interdependencies. In Figure 1 (below), we represent these stages diagrammatically.

Figure 1 Diagrammatical representation of adopted study approach

STAGES	Description
STAGE 1	This stage focuses on identifying the different activities constituting the project. We reviewed available documents provided by the project owner (including contract documents) and then consulted with an expert panel of consultants to identify the key project activities that constituted the design stage of the project.
STAGE 2	This stage entailed mapping the project activity interdependencies. The mapping was undertaken by expert panel comprising three of the four authors and three construction consultants. The outcome of this exercise was a Structural Self-Interaction Matrix (SSIM) adapted from Interpretive Structural Modelling (ISM) (Malone, 1975).
STAGE 3	This stage involved measuring the level of information interdependencies by assigning weight values to the relationships among activities.
STAGE 4	This stage involved converting the fuzzy adjacency matrix into a network comprising nodes and arcs (here, the nodes represent activities while arcs represent existence of information flows between these activities).
STAGE 5	This analysis stage employed the five identified metrics to analyse information flow interdependencies between directly and indirectly linked project activities.

4.1 Identification of activities

To demonstrate and validate our approach, we collaborated with a development organisation based in the UAE. The organisation ('Organisation A') is the main client of a major US$6.5 billion mixed-use residential development estimated to house approximately 75,000 new residents on completion. The identification of the activities commenced first with the authors reviewing the current outline plan for the project (which is in an evolutionary state). This led to the identification of approximately 64 different activities, which could be deemed as part of the project's design stage. Following this initial exercise, we (the authors) then consulted an expert panel group (consisting of three construction consultant practitioners) to further categorize these activities into 15 overall project-design activities. The expert group were drawn from a group of project management practitioners all with considerable working experience in the United Arab Emirates. In particular, all demonstrated significant professional technical and project management competency by being in possession of Chartered Engineer (CEng) as designated by the Engineering Council (United Kingdom). During both brainstorming sessions that formed the identification and categorization of activities, we employed simple face validity. To this extent, we adopted an approach previously utilised by Chipulu et al. (2019) in that categorization of the activities was based on a simple response of: '*not at all*' = '0', '*somewhat matches this activity group*' = '1' and '*very closely matches this activity group*' = 2. The 15 core project design activities which emerged from this process are shown in Table 1 (below).

Table 1: The identified project design activities

1. Conceptual Design	9. Power Systems Design

2. Schematic Design	10. Control and Low Current Systems Design
3. Architectural Design	11. Lighting Systems Design
4. Structural Design	12.Tendering Documentations
5. Foundation Design	13. Tendering and Bids Evaluation
6. Heating, Ventilation, and Air Conditioning (HVAC) Design	14. Production (Workshop) Design
7. Mechanical Systems Design	15. As-Built Documentation
8. Plumbing Systems Design	

4.2 Mapping of project design activity interdependencies

In a Structural Self-Interaction Matrix (SSIM), which we adapt from Interpretive Structural Modelling (ISM), we show the direction of information flow between project design activities *i* and *j*, as follows:

(i) ‘*V’* implies that project design activity *i* transmits information to project design activity *j* (a relationship which is forward);

(ii) ‘*A’* implies that project design activity *j* transmits information to project design activity *i* (a relationship which is backward);

(iii) ‘*X’* implies that project design activity *i* and project design team *j* exchange information (a relationship which is mutual), and

(iv) ‘*O’* implies that project design activity *i* and project design activity *j* do not exchange information (there is no relationship).

These relationships were identified from another brainstorming exercise in which we undertook dependency mapping following the preparation of a SSIM by the expert panel. This mapping is shown in Table 2, below.

Table 2. Structural Self-interaction Matrix

Activity	15	14	13	12	11	10	9	8	7	6	5	4	3	2
1	*O*	*V*	*V*	*V*	*V*	*V*	*V*	*V*	*V*	*V*	*V*	*V*	*V*	*V*
2	*O*	*V*	*V*	*V*	*V*	*V*	*V*	*V*	*V*	*V*	*V*	*V*	*V*	
3	*V*	*V*	*V*	*V*	*V*	*V*	*V*	*V*	*X*	*V*	*V*	*V*		
4	*V*	*V*	*V*	*V*	*V*	*X*	*A*	*X*	*A*	*A*	*X*			
5	*V*	*V*	*V*	*V*	*O*	*V*	*O*	*X*	*A*	*A*				
6	*V*	*V*	*V*	*V*	*O*	*V*	*V*	*V*	*V*					
7	*V*	*V*	*V*	*V*	*O*	*V*	*V*	*X*						
8	*V*	*V*	*V*	*V*	*O*	*V*	*V*							
9	*V*	*V*	*X*	*V*	*X*	*X*								
10	*V*	*V*	*V*	*V*	*A*									
11	*O*	*O*	*V*	*V*										
12	*O*	*V*	*V*											
13	*O*	*V*												
14	*V*													

The emergent SSIM was converted to a *n* x *n* adjacency matrix. Here *n* will signify the number of project design activities by replacing ‘*V’, ‘A’, ‘X’,* and/or ‘*0’* with 1s and 0s. The rubrics for the substitution are as follows:

(i) If the SSIM entry for (*i, j*) is ‘*V’*, then the adjacency matrix (*i, j*) entry will now become 1 while the entry for (*j, i*) now becomes 0;

(ii) If the SSIM entry for (*i, j*) is ‘*A’*, then the adjacency matrix (*i, j*) entry will now become 0 while the entry for (*j, i*) now becomes 1;

(iii) If the SSIM entry for (*i, j*) is ‘*X’*, then the adjacency matrix (*i, j*) entry will now become 1 while the entry for (*j, i*) now becomes 1;

(iv) If the SSIM entry for (*i, j*) is ‘*0’*, then the adjacency matrix (*i, j*) entry will now become 0 while the entry for (*j, i*) now becomes 0;

Implementing the substitutions shown above produced a binary matrix which we show in Table 3 (below).

Table 3. Binary adjacency matrix

Activity	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
1. Conceptual Design	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0
2. Schematic Design	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0
3. Architectural Design	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
4. Structural Design	0	0	0	0	1	0	0	1	0	1	1	1	1	1	1
5. Foundation Design	0	0	0	1	0	0	0	1	0	1	0	1	1	1	1
6. HVAC Design	0	0	0	1	1	0	1	1	1	1	0	1	1	1	1
7. Mechanical Systems Design	0	0	1	1	1	0	0	1	1	1	0	1	1	1	1
8. Plumbing Systems Design	0	0	0	1	1	0	1	0	1	1	0	1	1	1	1
9. Power Systems Design	0	0	0	1	0	0	0	0	0	1	1	1	1	1	1
10. Control and Low Current Systems Design	0	0	0	1	0	0	0	0	1	0	0	1	1	1	1
11. Lighting Systems Design	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0
12.Tendering Documentations	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
13. Tendering and Bids Evaluation	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
14. Production (Workshop) Design	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
15. As-Built Documentation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

4.3 Measuring the level of information interdependencies

The process of measuring the level of information interdependencies commenced with elements of values of '1's in the adjacency matrix (Table 3) being replaced with weights representing the level of information interdependencies based on the fuzzy set theory (Zadeh 1965, 1999), which allows for the the measured valuation of the involvement of elements in a set using a function of membership valued in the real unit interval [0, 1]. There are different shapes associated with these functions of membership. However, the literature indicates the most frequently used membership function to be triangular (Pedrycz 1994). Generally, the definition of the triangular function is articulated by setting out a minimum limit l, a maximum limit r, and an m value where $l < m < r$.

These points (that is *l, m*, and *r)* will generally denote the *x* coordinates of the three membership function vertices of "$\mu_{\tilde{A}}(x)$" in a fuzzy set *A*. We show this in Equation (1).

$$\mu_{\tilde{A}}(x) = \begin{bmatrix} 0 & x < l \\ \frac{x-l}{m-l} & l \le x \le m \\ \frac{r-x}{r-m} & m \le x \le r \\ 0 & x > r \end{bmatrix} \tag{1}$$

We assigned weight values to the relationships among the design activities as follows. Each expert panel provided their judgement on the levels of information interdependencies. For instance, in the adjacency matrix (Table 3), project design activity '3' (column 3) has information interdependencies on project design activities '1', '2' and '7' (rows 1, 2 and 7). This will mean that the project team members (arguably responsible for carrying out design activity 3) may employ linguistic variables which are shown in Table 4 to articulate their judgements on the levels of information interdependencies on project design activities '1', '2', and '7'. One means of assigning linguistic variables is to seek the consensus of each individual project team member on their validity. In this instance, they were asked to use these variables to offer their subjective views on the degree (level) of information interdependencies among the various design activities. Following this process, assigned linguistic variables were then changed into matching triangular *fuzzy* numbers which we show in Table 4. However, where this could not be achieved, every relationship that is in place between individual design activities could nonetheless be allocated a separate "*n*" triangular fuzzy number with *n* representing the quantity (in numerical terms) of members involved. The likely varying triangular fuzzy numbers can then if need be, be put together into a single triangular fuzzy number utilising the average score.

Table 4. Fuzzy linguistic scale

Linguistic variable	**Triangular fuzzy number**
No dependency	(0.0, 0.0, 0.0)
Very low dependency	(0.0, 0.1, 0.3)
Low dependency	(0.1, 0.3, 0.5)
Medium dependency	(0.3, 0.5, 0.7)
High dependency	(0.5, 0.7, 0.9)
Very high dependency	(0.7, 0.9, 1.0)
Complete dependency	(1.0, 1.0, 1.0)

On obtaining a triangular fuzzy number for level of interdependencies among individual project design activities (either by consensus or averaging), utilising a process of *defuzzification* of the triangular fuzzy numbers, a fuzzy adjacency matrix was then obtained, as shown in Equation (2),

$$BNP_{ij} = \frac{[(r-l)+(m-l)]}{3} + l\,, \tag{2}$$

Here, *BNP* denotes the value 'best non-fuzzy performance' and *ij* denotes the likely strength assessment for in-between factors *i* and *j*. This procedure for assigning linguistic variables to the relationships between project design activities was employed to develop the fuzzy adjacency matrix shown in Table 5.

Table 5. Fuzzy adjacency matrix

Activity	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
1. Conceptual Design	0	0.9	0.9	0.9	0.5	0.9	0.9	0.9	0.9	0.9	0.9	0.1	0.1	0.1	0
2. Schematic Design	0	0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.3	0.3	0
3. Architectural Design	0	0	0	0.9	0.9	0.9	0.9	0.7	0.9	0.7	0.9	0.9	0.9	0.9	0.7

4. Structural Design	0	0	0	0	0.9	0	0	0.3	0	0.9	0.5	0.9	0.3	0.9	0.7
5. Foundation Design	0	0	0	0.9	0	0	0	0.1	0	0.9	0	0.9	0.3	0.9	0.7
6. HVAC Design	0	0	0	0.7	0.7	0	0.9	0.5	0.9	0.9	0	0.9	0.3	0.9	0.7
7. Mechanical Systems Design	0	0	0.1	0.7	0.7	0	0	0.9	0.9	0.5	0	0.9	0.3	0.9	0.7
8. Plumbing Systems Design	0	0	0	0.1	0.3	0	0.1	0	0.3	0.1	0	0.9	0.3	0.9	0.7
9. Power Systems Design	0	0	0	0.5	0	0	0	0	0	0.9	0.9	0.9	0.3	0.7	0.5
10. Control and Low Current Systems Design	0	0	0	0.5	0	0	0	0	0.7	0	0	0.9	0.3	0.9	0.7
11. Lighting Systems Design	0	0	0	0	0	0	0	0	0.7	0.3	0	0.9	0.3	0	0
12.Tendering Documentations	0	0	0	0	0	0	0	0	0	0	0	0	0.9	0.7	0
13. Tendering and Bids Evaluation	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0
14. Production (Workshop) Design	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9
15. As-Built Documentations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

To account for indirect design activity interdependencies, repeated self-multiplication of the fuzzy adjacency matrix was undertaken until a stabilised matrix was secured. Multiplication was undertaken utilising fuzzy matrix multiplication principles (see Zadeh 1999). As shown in Equation (3), the outcome of fuzzy matrix *A* and fuzzy matrix *B* is fuzzy matrix *C*, thus:

$$C = A, B = \max k\ [(\min\ (a_{ik}, b_{kj})] \text{ where } A = [a_{ik}] \text{ and } B = [b_{kj}] \qquad (3)$$

The stabilised matrix shown in Table 6 was then obtained after four iterations.

Table 6. Stabilised fuzzy matrix

Activities	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
1. Conceptual Design	0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
2. Schematic Design	0	0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
3. Architectural Design	0	0	0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
4. Structural Design	0	0	0.1	0	0.9	0.1	0.1	0.3	0.7	0.9	0.7	0.9	0.9	0.9	0.9
5. Foundation Design	0	0	0.1	0.9	0	0.1	0.1	0.3	0.7	0.9	0.7	0.9	0.9	0.9	0.9
6. HVAC Design	0	0	0.1	0.7	0.7	0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
7. Mechanical Systems Design	0	0	0.1	0.7	0.7	0.1	0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
8. Plumbing Systems Design	0	0	0.1	0.3	0.3	0.1	0.1	0	0.3	0.3	0.3	0.9	0.9	0.9	0.9

9. Power Systems Design	0	0	0.1	0.5	0.5	0.1	0.1	0.3	0	0.9	0.9	0.9	0.9	0.9	0.9
10. Control and Low Current Systems Design	0	0	0.1	0.5	0.5	0.1	0.1	0.3	0.7	0	0.7	0.9	0.9	0.9	0.9
11. Lighting Systems Design	0	0	0.1	0.5	0.5	0.1	0.1	0.3	0.7	0.7	0	0.9	0.9	0.7	0.7
12.Tendering Documentations	0	0	0	0	0	0	0	0	0	0	0	0	0.9	0.7	0.7
13. Tendering and Bids Evaluation	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0.7
14. Production (Workshop) Design	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9
15. As-Built Documentation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

4.4 Network visualisation

Visualisation is a useful means of improving decision making in that it supports the detection and comparison of trends and patterns of information flows (Liu et al. 2014); in this case between project activities. In the case of our demonstration, we used *SocNetV* software visualization package to construct the network shown in Figure 2 (below).

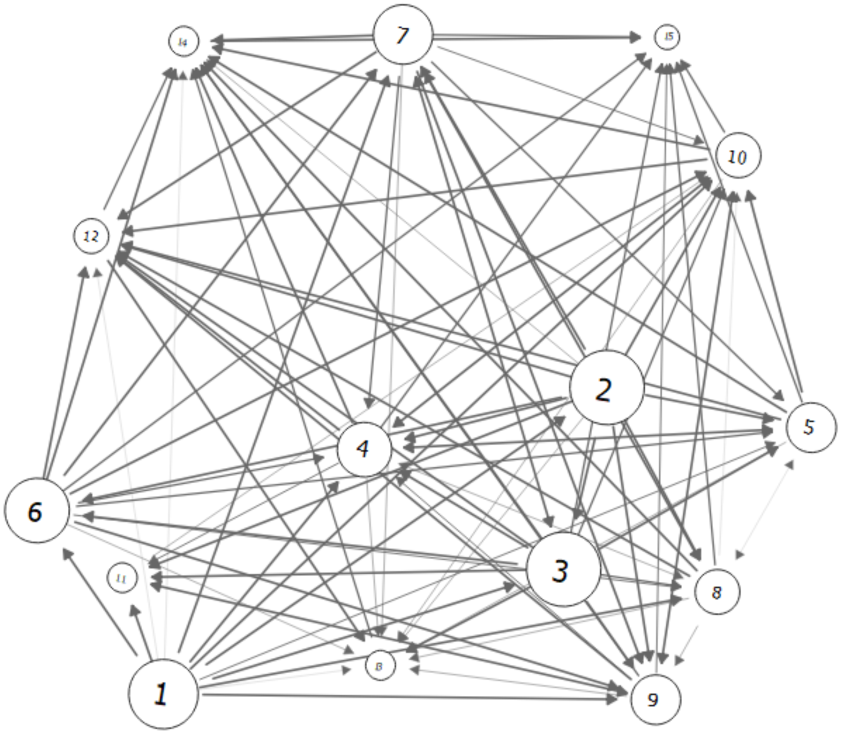

Figure 2: Activity interaction network

In the network diagram above (Figure 2), the lines between activities (which are unnumbered), denote the existence of relationships between the activities and the arrows in the lines show the direction of flow of information. The nodes have been sized to indicate corresponding '*Out-degree'* values. Thus, for example, based on the size of individual nodes, design activity 3 has the maximum '*Out-degree'* value. Note in particular that Figure 2 appears to offers some immediate practical management value. Specifically, it highlights activities two, three and (especially) four as information management focus areas where it may be sensible to concentrate information hubs or huddles dedicated to more effective sourcing, sharing and use of project information. However, the advantages of our more detailed analysis will become clear when it is shown that the focus areas we propose differ from this and are based on stronger grounds than centrality of activity interaction alone.

4.5 Analysis of information flow interdependencies

This next step involved analysing information flow interdependence between activities that are directly and indirectly related, based upon the five metrics mentioned earlier: '*Network density'*, '*In-degree centrality'*, '*Out-degree centrality'* (which are the three Network analysis metrics), '*Dependence power'* and '*Driving power'* (the two MICMAC metrics).

'*Network density'* (which assesses the number of relative ties between activities in a network) can be used for the assessment of the degree of information interdependencies between different project activities. In effect, the '*Network density'* metric provides a complexity indicator for the project network structure; that is, it can show how challenging it may be to manage the project. '*Network density'* was calculated by summating all entries of the fuzzy adjacency matrix (or summating the values of '*Out-degree'* or '*In-degree'*) and dividing the value by the total quantity (in numerical terms) of likely ties based on each individual node being tied to all other nodes. Mathematically, this measure can take any positive value in the range of '0' - '1'. If the value is '0', then no interrelationships exist between the activities. If the value is '1', then each activity has a complete association with each of the others. In this study, the network density was computed to be 0.10, suggesting that the network structure which we studied is of low complexity.

The '*In-degree centrality'* of activity *j* can be used to quantify the overall degree of information interdependencies of directly related design activities. Computation was undertaken by summing up the entire values of column *j* within the fuzzy adjacency matrix. The total level of information dependency for specific sets of design activities against a directly related activity *i* was quantified using '*Out-degree* centrality*'*. This was computed by summing all values of row *i* of the fuzzy adjacency matrix.

The '*Dependence power'* of design activity *j* was used to quantify its total level of information interdependencies on directly and or indirectly linked design activities by computing the sum of all the values of column *j* of the MICMAC-stabilised matrix. The total level of information interdependencies of design activities on a particular directly or indirectly linked design activity *i* was quantified using the '*Driving power'* by computing the sum of all the values of row *i* of the MICMAC-stabilised matrix. Accordingly, our computed values for '*In-degree centrality'*, '*Out-degree centrality'*, '*Dependence power'*, and '*Driving power'* are shown in Table 7.

Table 7. The computed values of metrics of interrelationships

Activity	In-degree Centrality	Out-degree Centrality	Dependence Power	Driving Power
1	0.0	8.9	0.0	12.6
2	0.9	9.6	0.9	11.7
3	1.9	10.2	2.6	10.8
4	6.1	5.4	6.8	7.4
5	4.9	4.7	6.8	7.4
6	2.7	7.4	3.4	9.6
7	3.7	6.6	4.2	8.8
8	4.3	3.7	6.0	5.4
9	6.2	4.7	7.6	7
10	7.0	4.0	8.2	6.6
11	4.1	2.2	7.8	6.2
12	9.1	1.6	9.9	2.3
13	4.6	0.7	10.8	1.4
14	8.8	0.9	11.1	0.9
15	6.3	0.0	12.0	0

The next step was to classify the design activities by dependency level into four main categories of 'importance': 'A' (*mostly*), 'B' (*moderately*), 'C' (*slightly*), and 'D' (*leastly*). Two activity types fell into each category with the first, which we called 'Type I', comprising activities whose importance was determined on the basis of their '*In-degree centrality*' and '*Out-degree centrality*' values. Conversely, the 'Type II' category comprised activities designated on the basis of '*Driving power*' and '*Dependence power*' values. This classification was undertaken through the development of a diagram for both '*Out-In-degree centrality*' and '*Driving-Dependence power*'. The '*Out-In-degree centrality*' diagram was developed by a plot of '*Out-degree centrality*' values against values for '*In-degree centrality*', followed by a division of the diagram into four quadrants.

5. Results

The design activities within the first quarter are observed as having '*Out-degree centrality*' and '*In-degree centrality*' values which are both high. These design activities are classified under a category labelled as Class A-type I. Design activities within the second quarter also exhibit '*Out-degree centrality'* values, which are high, but with '*In-degree centrality'* values, which are low. We designate these as Class B-type I. Design activities in the third quarter have '*Out-degree centrality'* values which are low, but '*In-degree centrality'* values, which are high. We classify these as Class C-type I. Finally, the design activities within the fourth quarter have values for '*Out-degree centrality'* and '*In-degree centrality', which* are both low. These are denoted as Class D-type I.

In the same manner, the '*Driving-Dependence power'* diagram is developed by first plotting the values of '*Driving power'* against that of '*Dependence power'.* This is then followed by then splitting the diagram into four quadrants. In the first quarter are project activities with '*Driving power'* and '*Dependence power'* values that are both high. These design activities are classified into a category designated as Class A-type II. In the second quarter are design activities with high '*Driving power'* values, but low '*Dependence power'* values. These activities are classed as Class B-type II. The third quarter contains design activities with low '*Driving power'* values but high '*Dependence power'* values. These activities are classified as Class C-type II. Finally, design activities in the fourth quarter have low '*Driving power'* and '*Dependence power'* values. These activities are labelled as Class D-type II.

The '*Out-In-degree centrality'* and '*Driving-Dependence power'* diagrams are shown in Figures 3 and 4, respectively. From Figure 2, we observe that there is only one activity, namely activity 4 ('*Structural Design'*) of Class A-type I (where project activities have high '*Out-degree centrality'* and '*In-degree centrality'* values). On the other hand, from Figure 3, the Class A-type II (where project activities have high '*Driving power'* and '*Dependence power'* values) activities are 4 (‘*Structural Design’*), 5 (‘*Foundation Design’*), 9 (‘*Power Systems Design’*), and 10 (‘*Control and Low Current Systems Design’*).

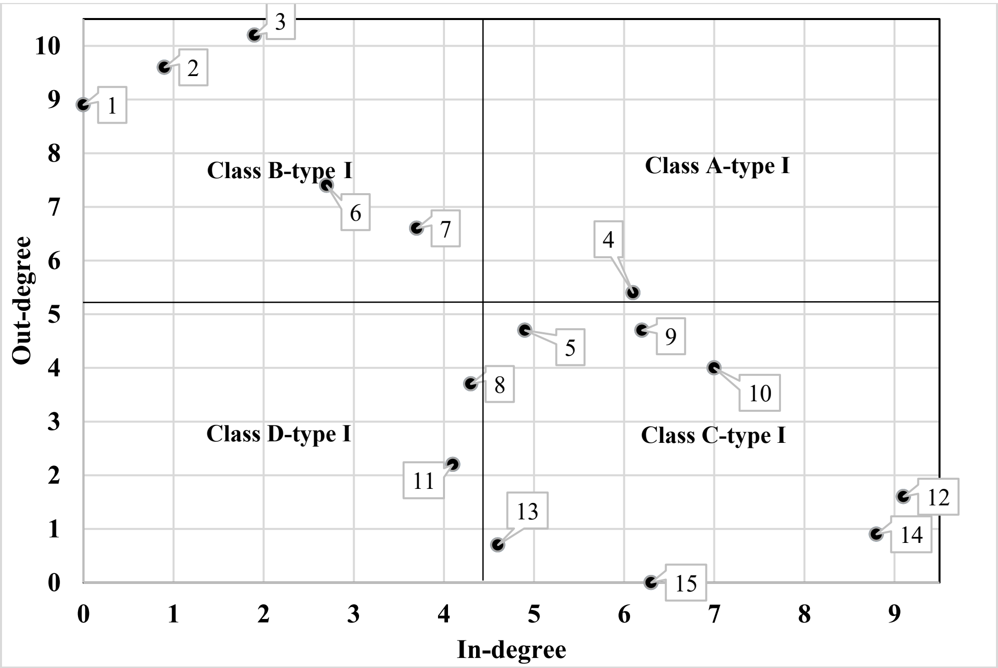

Figure 3. ‘*Out-in-degree centrality’*

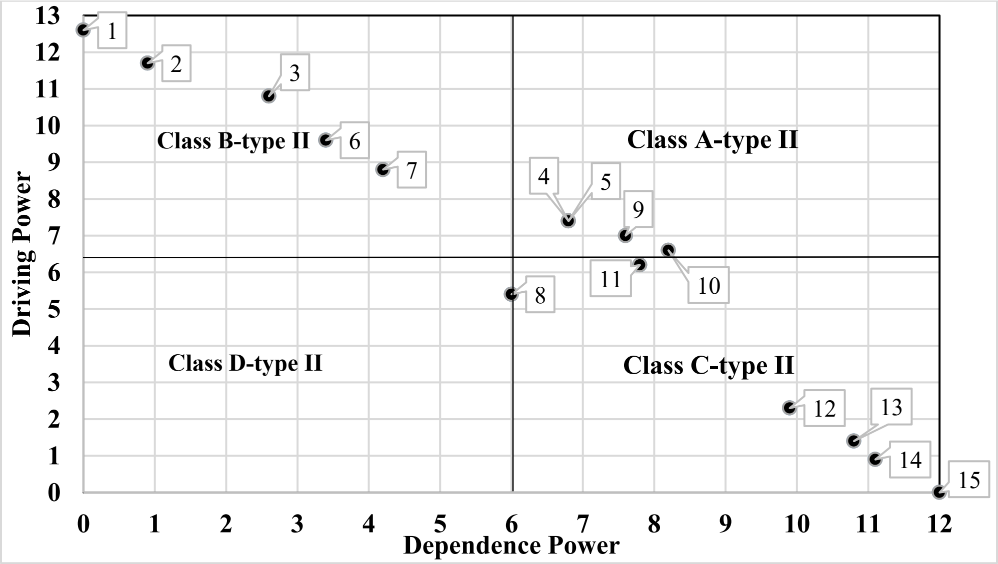

Figure 4. *'Driving-dependence power'*

In effect, the above mentioned activities (4, 5, 9 and 10) can be considered critical; more specifically, they emerge strongly from the analysis as focus areas for creating information hubs and huddles where managers from across projects can usefully participate to ensure optimal harnessing and exploitation of the information at issue.. Activity 4 ('*Structural Design*') warrants particular mention as it appears under both Class A-type I and Class A-type II categories.

6. Discussion

In this study, we analysed a network of design activities in projects using an integrated form of Network Analysis augmented with *fuzzy* Cross-impact Matrix Multiplication Analysis in order to facilitate an understanding the pattern of information flow exchange in in major project setting. The advantage that comes from the use of this approach is that it facilitates the analysis of not only project activity interdependencies, but also classifies these activities based on their dependency levels with other directly and indirectly linked project activities. The approach, in effect, allows for the intricate relationships between different project activities to be determined. It appears logical to assert that the five metrics, that is '*Network density*', '*In-degree centrality*', '*Out-degree centrality*', '*Dependence power*' and '*Driving power*' serve as means by which we are able to assess the depth of interrelationship between project activities and by implication, nature of information flow between and across highly distributed, co-located, self-organizing and networked projects. When information flow is effective and efficient, it is assumed that the quality of relationships between the project team assessed by the degree or extent of more close and collaborative working, increases (Ojiako et al. 2015). Accordingly, our findings can be valued as highlighting activity focal points within projects (especially 'structural design' activity) that may merit collaborative information management for the benefit of all contributing parties.

Application of the approach further allowed for the ascertaining of the degree of the relationship between the various design activities in three ways. *First*, four main categories of dependency levels – namely, 'A' (*mostly*), 'B' (*moderately*), 'C' (*slightly*), and 'D' (*leastly*); and *second*, against dependency levels with 'Type I' including those activities which are determined on the basis of their '*In-degree centrality'* and '*Out-degree centrality'*, values while 'Type II' categories included those activities designated on the basis of the value of '*Driving power'* and '*Dependence power'*. Finally (*third*), interdependencies were assessed against two groups of different activity classifications – namely, '*In-degree centrality'* versus '*Out-degree centrality'* (Class A-type I, Class B-type I, Class C-type I and Class D-type I activities) and '*Driving power'* versus '*Dependence power'* (Class A-type II, Class B-type II, Class C-type II and Class D-type II). Furthermore, the value of our novel categorisations (A to D) and classifications (I or II) is that they can conceivably be used as visual frameworks for ranking and monitoring project activities for their information exchange salience. This may be valuable within the contexts of planning/scheduling for formal information hubs, and for deciding where to focus more informal and *ad hoc* information huddles as projects progress. With reference to the former, understanding information interdependencies is of strong practical relevance from a sequencing perspective in infrastructure project planning. For example, it becomes possible to commence project activities that are dependent on information from other activities if the available information lies within parameters that are predicable. In effect, this allows a project activity to commence based on a 'safe' approximation to expected information flows. Of course, the design stages of most infrastructure projects are nonetheless iterative and will involve designer managers from various specialist groups. That is why our findings are also important from the perspective of the support they offer for *ad hoc* design of informal information huddles. Looking closer, a key consideration is that such design input will, very rarely take a holistic view of the project. More often than not, ad hoc views of the project will be from narrow practice (discipline-based and experiential) perspectives. Hence, our proposals for monitoring and ranking activities for their information flow salience can stand in place of holistic project views to offer an immediately accessible reference point for designing *ad hoc* information huddles.

Our study has also emphasised the importance of careful design and information management focused on what can be termed 'linkage activities' within projects. With reference to their high '*Driving power'* and '*Dependence power'*, and further drawing from earlier studies by Tavakolan and Etemadinia (2017), activities '4', '5' and '9' are indeed describable as "…*linkage activities*" (p 5.) These are basically activities with extremely high levels of instability, entailing a high susceptibility to iterative and *ad hoc* re-design aimed at mitigating harmful impacts and seizing opportunities

Accordingly, we conclude that our findings not only reiterate the critical role of both preliminary and ongoing/iterative design stages in infrastructure projects, as already expressed in the literature (see Jrade and Jalaei 2013; Ajayi and Oyedele 2018), but also highlight the methods and rationales available for managing information flows associated with both Class A-type I and Class A-type II activities in particular. Visualising and ranking project activities in terms of these classes and types provides a viable means, we would suggest, for focusing management attention towards information exchanges characterised by a high degree of accuracy, scope, detail and timeliness. Crucially, we would suggest that these attributes further entail that the information in question is particularly likely to offer latent value that might be more fully exploited via information hub/huddle dissemination across projects. The need for such wider dissemination can reasonably be theorised with reference to the well-understood mechanism whereby as the level of project network structure complexity increases, the more challenging its management becomes (Luo et al. 2016). When projects are faced with managing intricate functional interrelationships during design iterations it is therefore likely that they will seek to widen the information that is made available to all teams involved in the delivery. However, roll outs of ever-increasing information volume require decisions about prioritisation and sequencing. Our findings help by drawing attention to what information is best prioritised for wider dissemination, as well as how it is best disseminated, so as not to simply provide a confusing and unfiltered excess of information which may cause overload. As those who manage specific activities in projects are most likely to share information with those in close proximity, we recognise that it may be particularly beneficial to widen information flows and exchanges via these pathways, which is to say, in effect, through agreements made among managers who have formed the hubs and huddles we advocate for, and who have worked within these structures to develop a shared trust, both in each other and in the information they exchange. A leader-follower system of trust-in-information can be encouraged to operate thereafter, whereby managers across a project are encouraged to trust information by following the rationale whereby the case for its wider availability has already been determined within information hubs and huddles, which have already scrutinised the information carefully from multiple perspectives.

Our finding that the core design activities in the case project are associated with a high level of information interdependency also resonates with academic literature. Generally, it is acknowledged that the design stage of infrastructure projects entails significant information exchange (Aurich et al. 2006; Jrade and Jalaei 2013). Thus, effective information exchange can be construed as a fundamental requirement of successful infrastructure project delivery. Because design activities arguably reside within an information cluster, failure of management to effectively manage them can, in addition to quality failures, lead to time and cost overruns in the entire project. Arguably, design activities can be considered critical as they contribute extensively to activity completion times (Joao et al. 2012) and we would further suggest that such design activity should be the focus for the information hubs and huddles we advocate for above.

7. Conclusions

What was of interest to this study was the desire to facilitate not only greater understanding of information flow interdependencies between project activities, but also to do so in a manner that allowed for these activities to be classified based on their degree of interdependency. A systematic and detailed understanding of information flows at the development stage of projects has been shown to be of paramount importance in project settings (Parraguez et al. 2015). Despite this being the case, prior project management research focused on the design stage of projects have paid limited particular attention to analysing information flows based on activity interdependency in a manner that analyses such flow based on the directly and indirectly linked project activities. For these reasons, it was extremely pertinent to undertake this study. We advance three reasons. *First*, understanding such information flow supports optimised project scheduling in that it provides project management practitioners with an overview of the nature of interdependencies and interactions between project activities. It also brings critical activities to the attention of those managers. *Second*, as a review of literature showed, existing project scheduling models have been limited in their inability to condition the influence of vagueness and uncertainty on multi-level activity interdependencies. *Third* (and finally), recent works of scholarship looking to set the agenda for project management research appear to suggest the need not only for increased emphasis on non-deterministic time-based perspectives of project scheduling (Padalkar and Gopinath, 2016), but also for research which is aptly able to reconcile the requirement for theory development with practitioner engagement in infrastructure management (Schweber, 2015; Kanjanabootra and Corbitt, 2016).

This study commenced on the premise that traditional scheduling tools exhibited manifested limitation in terms of their ability to articulate interdependencies between different activities. In order to facilitate analysis of project activity interdependencies and at the same time classify project activities using dependency levels, we proposed and developed an approach that integrated Network analysis with *fuzzy* MICMAC. Most importantly, this approach will not only support the analysis of project activity interdependencies, but will also serve to classify project activities against dependency levels with directly and indirectly linked activities using two categorisations (Class A-type I and Class A-type II) labelled against four metrics ('*In-degree centrality*', '*Out-degree centrality*', '*Dependence power'* and '*Driving power'*). These metrics provide project managers with the ability to prioritise and closely monitor activities deemed to be of high importance.

Our proposed approach provides project managers – and in particular those who opt to work within information hubs and huddles - with the capacity to understand not just the nature of the interrelationships between different project activities but also how concurrency can be enhanced while mitigating against potential adverse consequences emerging from multi-level activity interdependencies at the same time. Our proposed approach also resulted in the development of a classification system, which allows for critical project activities to be categorised by the level of direct and indirect information interdependencies between different activities. Arguably, among other outcomes, such a classification may support more effective resource allocation, particularly in multiple workflow environments where project activities are expected to be executed concurrently.

As may be expected, the study does have a number of limitations, which creates opportunities for further research. The first of these concerns the need for further work to establish generic terms of reference for the hubs and huddles we advocate for, not least in order to clarify the combined design and information exchange functions which we envision as central to their functioning. To progress our advocacy of informal huddles in particular, it is notable that we did we make any provisions for activity flexibility such as might routinize the creation and recreation of non-routine and potentially disruptive project structures (and by implication, activities) around project requirements (see Ligthart et al. 2016). Our second major limitation concerns our assumption, despite available literature to the contrary (see, as an example, Hwang et al. 2016), that levels of information interdependencies between the various project activities will remain relatively fixed throughout project execution. Arguably, a more dynamic and predictive approach to assessing project activities may overcome this. As a third limitation, two of the steps we employed in our approach development steps, '*mapping of interdependencies*' and '*measuring the level of information interdependencies*', were undertaken manually (due to the relatively limited number of activities in the project plan). However, in infrastructure projects, undertaking both steps manually will require significant human effort and, thus, this approach may not necessarily be feasible. A recent study by Isaac et al. (2017) appears to suggest that Building Information Modelling (BIM) can be employed to automate workflow analysis. A fourth limitation is as follows. As posited by Dubey and Ali (2014), ISM is a subjectivity-laden tool. More recently, noting this limitation, approaches such as Total Interpretive Structural Modelling (TISM) have been proposed and used (Prasad and Suri, 2011; Sushil, 2012; Singh and Sushil, 2013). Finally, as a fifth limitation, the study did not take into consideration the possibility that other network analysis metrics exist in addition to the three we developed and employed in the present paper: '*Network density*', '*In-degree centrality*', and '*Out-degree centrality*'. The limitation also applies to our reliance on two MICMAC metrics: '*Dependence power*' and '*Driving power*'. By conceiving of interdependence firmly with further reference to a power construct, it is likely that our study may have omitted other plausible means of assessing interdependence. Thus, further studies might begin to postulate that there are other forms of activity interdependence that may have an impact upon the information flows and the resultant degree of interaction project teams delivering infrastructure projects will require. On identifying 'embeddedness' (see Uzzi, 1996, 1997), as another plausible means of assessing interdependence (in an interorganizational context), two such likely measures which Gulati and Sytch (2007) identify in their study are '*Dependence asymmetry*' which they define as "*…the difference in actors' dependencies on each other in a dyadic exchange relationship*" (p.32), and '*Joint dependence*', which they define as "*the sum of dependence between actors in the relationship*" (p. 32). Thus, future studies may focus on the analysis of project activity interdependencies using either additional metric.

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