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A comparison of project control standards based on network analysis

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Abstract:
Project control is a crucial function in project management. Over the years, several best practice standards have been developed to assist project managers in improving project control. The objective of this paper is to compare three prominent best practice models of PMBOK, PRINCE2, and the AACE framework with respect to the core processes of project control. Network analysis is used to achieve this objective. The results show that influential and linkage processes, such as Control quality, Review the stage status, Forecasting, and Change management have the most significant impacts on the complexity of the project control function. This work has the potential to help rethink the project control function by creating a more global view of the most central and critical processes for project control, from which enhancement in the ability to control the project can be drawn.

Keywords:
project management; project control; PMBOK; PRINCE2; AACE; network analysis.

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1. Introduction

The role of monitoring and control in project management is to detect potential problems during project execution and to take necessary corrective actions to achieve project performance objectives. Some such objectives are ensuring the schedule and budget are adhered to. Recent studies have, moreover, shown that project control is an essential function towards project success ([1]-[3]). Projects are completed to quality, cost, schedule, and health and safety regulations when monitoring and control is implemented effectively.

Given the essential function of project control in project management, different methodologies, such as PMBOK (Project Management Body of Knowledge) and PRINCE2 (PRojects IN Controlled Environments), and their underlying tools, techniques, and processes have been increasingly adopted by project managers to plan, execute, monitor, and control activities in order to ensure project delivery [4]. Although these project management methodologies share overlapping content, each of the standards offers different advantages. Over the years, several researchers tried to unify the tools, techniques, and practices of various project management standards by integrating and harmonizing different standards so as to implement project management processes more effectively and efficiently ([5]-[9]).

In this paper, network analysis is used to analyze the three standards of PMBOK, PRINCE2, and AACE (Association for the Advancement of Cost Engineering) for the control of projects. Network analysis is an analytical technique evolving from graph theory used in multiple fields including social sciences, natural sciences, construction management, and safety [10]. In construction management, researchers use network analysis in various ways ranging from organizational analysis to team interactions in a construction project [11]. For example, the use of network analysis is gaining popularity in organizational governance and project management and has the potential to map temporal construction project-based organizations as networks to examine the interactions between stakeholders within the network boundary [12]. Network analysis is also used to investigate the structure of a network where nodes represent parties or team members and links represent the relationships between them [11].

In a previous paper [13], we used network analysis to characterize the most central processes of the two standards of PMBOK and PRINCE2 for the control of projects. In this paper, we propose to extend the analysis by examining and comparing PMBOK, PRINCE2, and AACE control processes in order to identify their most central and critical processes. The characterization of central features of project control within each standard will be achieved using network analysis.

The reminder of this paper is organized as follows. Section 2 provides an overview of recent work in the fields of project control and network analysis. Section 3 presents the three project control standards – PMBOK, PRINCE2, and AACE – the methodology for constructing the associated network models, and the statistical measures to analyze them. In Section 4, the three network models are analyzed and the key processes of project control are categorized. Conclusions are finally drawn in Section 5.

2. Literature background

2.1 *Project control and project management standards*

Project control is a critical function in project management. Project control evaluates actual performance and resolving any deviations from planned performance during project execution. This is a significant phase towards project success. To facilitate project control, quantifiable performance metrics are typically defined before a project starts. These metrics reflect the critical success factors as well as project objectives, such as cost, time, quality, safety, productivity, and scope of work.

Recently, Al-Tmeemy and Al Bassam [1] showed that cost of control activities significantly enhance project management success in terms of adherence to budget, schedule, and quality target. Demachkieh and Abdul-Malak [2] confirmed the relevance for enhancing the efforts, systems, or mechanisms required for implementing effective monitoring and control for the success of projects in all industries. The benefits of project monitoring and evaluation has also been demonstrated by Callistus and Clinton [3] who emphasized the critical role of monitoring and control in the management of construction projects throughout the entire life cycle of project delivery. For a more thorough review of project control, the interested reader is referred to the recent work of Pellerin and Perrier [14].

To ensure the delivery of a project, project managers need to utilize proper project management methodologies. Nowadays, many standard methodologies on project management are available [15]. Standards worth mentioning include PMBOK, PRINCE2, ISO, BS 7000-2:2008, APMBOK, and ICB. Recently, some of these standards, e.g., PMBOK and PRINCE2, have been demonstrated to be useful to either effectively evaluate an organization's current project management maturity level (e.g., [16],[17]) or to apply project-based processes for the implementation of change management initiatives [18]. Others, like the AACE (Total Cost Management) framework for project control plan implementation, have been used to classify the current literature in the context of organizations involved in the social economy and solidarity economy [19]. These project management methodologies have also been continuously refined to reflect advances in project management knowledge database [16] and to facilitate the communication, the understanding, and the application of these standards [4].

Given that each standard methodology has its own strengths and limitations, several authors recommended using different standards as complementary to each other. Also, researchers tried over the years to create a unified methodology proposal that integrates the strengths of two or more best practices. For example, von Wangenheim et al. [5] proposed a unified set of best practices for project management by integrating PMBOK and CMMI (Capability Maturity Model Integration) models. Madani [6] designed a framework to integrate knowledge management and PMBOK processes. Mesquida et al. [7] used the PMBOK guide to complement the ISO/IEC 29110-5-1-2 standard. Brioso [8] suggested that the management standards used in construction, such as the PMBOK and PRINCE2, among others, may be made compatible through the ISO 21500 standard to allow sequences and the adaptation of processes to be carried out in a flexible way. More recently, Isacas-Ojeda et al. [9] presented an integrated model for managing civil construction projects based on the best practices of the PMBOK and international standards governed by ISO 21500 in project management.

2.2 *Network analysis*

Based on sociometrics and graph theory, network analysis uses statistical tools to analyze the impacts of nodes (e.g., actors or parties) and links (e.g., interactions between different nodes) in a particular network and to help understand the network relationship through describing, visualizing, and statistical modeling ([11],[20],[21]).

Along with its dominant use in sociology and organizational research, network analysis has been used in a variety of disciplines including electrical power grids, wastewater, transportation, communication, biology and medical, and ecological [11]. Network analysis has also become increasingly popular in different areas of construction management research over the last two decades, including the areas of supply chain management, on-site operational management, and health and safety issues [11],[12]. One theoretical bridge to using network analysis in construction is to view construction project-based organizations as a set of networks. Network analysis provides a way to represent and understand project-based organizations by translating them into networks thus allowing innovative studies of organizational relationships [12]. In recent years, the use of network analysis to study project-based organizations in the construction sector has increased [22].

Specifically, network analysis has been applied to project management for the purposes of analyzing interdependencies within a project portfolio [23], examining the relationship between project performance and organizational characteristics in construction companies [22], as well as identifying the major risks embedded either across the supply chains of prefabricated building projects [24] or in international construction projects [25]. Network analysis has additionally been applied in construction projects to identify and model actual social structures, project team interactions, and collaborative project management ([11],[12],[20],[21],[26]) and also to enable the detection of relationships between causes of fatal accidents [10].

3. Project control standards and network centrality measures

In this section, we briefly review the main project control concepts introduced by three widely used standard and structured project management methodologies: PMBOK, PRINCE2, and the AACE framework. We then present the type of network representation that can be used to model these three standards and introduce the statistical measures to analyze them.

3.1 Project control standards

Several best practice models related to project management provide specific guidelines for controlling projects and describe the related processes. In this respect, PMBOK, PRINCE2, and the AACE framework represent three collections of best practices that have a project control focus. First, PMBOK (Project Management Body of Knowledge) is a classic project management methodology developed by the Project Management Institute [27]. In PMBOK, project management is accomplished through the application and integration of 47 project management processes that cover the entire project life cycle, from proposal to delivery, final acceptance, and closing. Among these, eleven monitoring and controlling processes are required to track, review, and regulate the progress and performance of the project, identify any areas in which changes to the plan are required, and initiate the corresponding changes (Table 1). Each control process in PMBOK is characterized by its inputs and the resulting outputs to meet the objective of the process (for the detailed inputs and outputs, please refer to Table 4 in Appendix A).

Table 1. PMBOK project monitoring and controlling processes

Process	**Description**
Monitor and control project work	Tracks, reviews, and reports the progress to meet the performance objectives defined in the project management plan
Perform integrated change control	Reviews all requests for changes or modifications to project documents, deliverables, baselines, or the project management plan, and approves or rejects the changes
Validate scope	Formalizes acceptance of the completed project deliverables
Control scope	Monitors the status of the project and product scope and manages changes to the scope baseline
Control schedule	Monitors the status of project activities to update project progress and manage changes to the schedule baseline to achieve the plan
Control costs	Monitors the status of the project to update the project costs and manages changes to the cost baseline
Control quality	Monitors and records results of executing the quality activities to assess performance and recommend necessary changes
Control communications	Monitors and controls communications throughout the entire project life cycle to ensure the information needs of the project stakeholders are met
Control risks	Implements risk response plans, tracks identified risks, monitors residual risks, identifies new risks, and evaluates risk process effectiveness throughout the project
Control procurement	Manages procurement relationships, monitors contract performance, and makes changes and corrections to contracts as appropriate
Control stakeholder engagement	Monitors overall project stakeholder relationships and adjusts strategies and plans for engaging stakeholders

Similarly, PRINCE2 is a process-based methodology for the definition, execution, and monitoring of projects that has been introduced by the UK's Office of Government Commerce. PRINCE2 contains seven inter-linked major processes, including one project control process that is a set of eight activities to be undertaken during the project life cycle. The project control process in PRINCE2 ensures that project objectives are met by measuring progress and taking corrective actions when necessary. This process includes collecting project progress status, analyzing variances, and communicating project status. Table 2 shows the eight project control activities in PRINCE2 [28]. Each control activity has its corresponding inputs and outputs, 41 in all (see Table 5 in Appendix A).

Table 2. PRINCE2 project control activities: inputs (I) and outputs (O)

Activity	Description
Authorize a work package	Assigns and agrees a work package with the team manager
Review work packages status	Checks on work package progress
Receive completed work package	Checks quality and configuration management
Review the stage status	Continually compares status to stage plan
Report highlights	Regular reports to the project board
Capture and examine issues and risks	Categorizes and assesses impact
Escalate issues and risks	Creates exception report and sends to the project board
Take corrective action	Solves issue or risk while keeping stage within tolerance

With a great focus on project control, the AACE framework is an integrated approach to portfolio program and project management introduced by the Association for the Advancement of Cost Engineering International. The distinguishing feature of the AACE model is that it offers a systematic approach to managing cost throughout the life cycle of a project while using Deming's wheel of quality (Plan-Do-Check-Act) to pinpoint and categorize activities. The AACE standard defines four project control processes divided into thirteen sub-processes. Table 3 presents the AACE model's project control processes and sub-processes [29]. All processes and sub-processes interact with one another through inputs and outputs (see Table 6 in Appendix A).

Table 3. AACE project control processes and sub-processes

Processes	Sub-processes	Description
Project control planning	Project scope and execution strategy development	Translates the project implementation basis (i.e., asset scope, objectives, constraints, and assumptions) into controllable project scope definition and an execution strategy that establishes criteria for how the work will be implemented.
	Schedule planning and development	How plans develop over time in consideration of the costs and resources for that work.
	Cost estimating and budgeting	Quantifies, costs, and prices the resources required by the scope of an investment option, activity, or project, and allocates the estimated cost of resources into cost accounts (i.e., the budget) against which cost performance will be measured and assessed.
	Resource planning	Ensures that labor, materials, tools, and consumables, which are often limited in availability or limited by density, are invested in a project over time in a way that successfully, if not optimally, achieves project objectives and requirements.
	Value analysis and engineering	Improves the value for the intended asset or project objectives as defined by the respective strategic asset requirements or project implementation basis inputs.
	Risk management	Establishes objectives, identifies risk drivers occurring throughout the project or asset lifecycle, and essentially manages that risk by continually seeking to assess, treat and control their impacts.
	Procurement planning	Ensures that information about resources (e.g., labor, material, etc.) as required for project control is identified for, incorporated in, and obtained through the procurement process.

Processes	Sub-processes	Description
Project control plan implementation	–	Integrates all aspects of the project control plan; validates that the plans are comprehensive and consistent with requirements and ready for control; initiates mechanisms or systems for project control; and communicates the integrated project control plan to those responsible for the project's work packages.
Project control measurement	Project cost accounting	Measures and reports the commitment and expenditure of money on a project.
	Progress and performance measurement	Measures the expenditure or status of non-monetary resources on a project (e.g., tracking the receipt of materials or consumption of labor hours) and the degree of completion or status of project work packages or deliverables (e.g., the extent that materials have been installed, deliverables completed, or milestones achieved), as well as observations of how work is being performed (e.g., work sampling).
Project control performance assessment	Project performance assessment	Compares actual project performance against planned performance and identifying variances from planned performance.
	Forecasting	Evaluates project control plans and control baselines in consideration of assessments of ongoing project performance.
	Change management	Manages any change to the scope of work and/or any deviation, performance trend, or change to an approved or baseline project control plan.
	Project historical database management	Collects, maintains, and analyzes project historical information so that it is ready for use by the other project control processes and for strategic asset management.

3.2 Network representation and centrality measures

Network analysis is used in this paper to identify the central processes of three project control standards: PMBOK, PRINCE2, and the AACE framework. The actual structure of each project control standard can be modeled by a directed graph $G = (V, A)$ where $V = \{v_1, v_2,..., v_n\}$ is the vertex set and $A = \{(v_i, v_j) : v_i, v_j \in V \text{ and } i \neq j\}$ is the arc set. Vertices v_1, v_2,..., v_n correspond to processes, sub-processes, inputs or outputs. Arcs are used to represent relationships between vertices, namely the inputs and outputs of each process or sub-process. Specifically, if v_j is a process and (v_i, v_j) and (v_j, v_k) are two arcs connecting pairs of vertices, then the vertices v_i and v_k are called the input and output of the process v_j, respectively.

In network analysis, measures of centrality are key statistical indices to identify the most important vertices in a network ([10],[20]). Three centrality metrics were used in this research: degree centrality, betweenness centrality, and closeness centrality. The higher the centrality value represents a more core position of a vertex in a network and reveals the greater extent to a vertex affects others [21]. Degree centrality is an indicator of the extent to which a vertex depends on others, or to which other vertices are dependent upon it [23]. A vertex with a large number of incoming arcs transmitted to it is highly dependent on other vertices and is said to have high *indegree* centrality. Similarly, a vertex with high *outdegree* centrality emits a large number of outgoing arcs and has many vertices dependent on it. Therefore, the indegree centrality can be seen as a measure of dependence or support, while the outdegree centrality can be considered as a measure of independence or influence [30].

Another way to measure the importance of a vertex is to examine the extent to which a vertex is located upon the geodesic distance or shortest path between every pair of the remaining vertices [23].(The shortest path from one vertex to another is the sequence of arcs connecting between these two vertices and consisting of the least number of arcs). This measure, called *betweenness* centrality, has been linked for example to the potential control and impact that a vertex can exercise in the network [20], the intermediary, channelling and mediating functions in controlling and transferring information flows within the network ([12],[23],[31]), as well as how influential a particular vertex is within the network [10]. A high betweenness centrality vertex has more control within the network, assuming more information is flowing through that vertex, and greater capacity to influence the other vertices [20]. Vertices with high betweenness centrality are the hubs in the network to connect many pairs of vertices and consequently lead to impact propagation and complex vertex interactions across the network [24]. Therefore, these vertices should be monitored to reduce the complexity of the network.

Finally, the *closeness* centrality measure describes the ability to reach a vertex in a network. Formally, this measure can be defined as the inverse of the average length of the shortest paths from all vertices to a given vertex in the network. A higher closeness centrality vertex has thus the ability to quickly acquire information through the other vertices [32]. In some way, the closeness centrality measure denotes the degree of autonomy or independence of a vertex ([20],[21]).

4. Results

This section examines the three networks of PMBOK, PRINCE2, and AACE for project control. For each of the three project control standards, a network model is first developed to pinpoint the core processes of the network. The results of the three models are then interpreted and validated through network centrality measures to identify the key processes of project control and the interrelationships among them. The three network models were constructed and analyzed in *R* (version 3.2.4) using the networkD3 package. The Fruchterman-Reingold force-directed layout algorithm was used for visualizing the networks [33]. In this algorithm, vertex layout is determined by simulating the whole graph as a physical system. Arcs in the graph are seen as springs binding vertices. Vertices are pulled closer together or pushed further apart according to attractive and repulsive forces, respectively. The objective of the algorithm is to minimize the overall energy of the whole system by adjusting the positions of the vertices and changing the physical forces between them to achieve an aesthetically pleasing graph layout.

4.1 Network models

Figures 1, 2, and 3 graphically display the PMBOK, the PRINCE2, and the AACE networks, respectively. The vertex numbers follow the numbering of the information presented in Appendix A in Tables 4, 5, and 6, respectively. Vertex size reflects the number of arcs incident to a vertex (degree centrality value). Thus, a large-size vertex represents the prominence of the vertex. Also, processes in the center of a network represent core items to the project control network. Core items should be controlled first, while the other peripheral items can be discarded or controlled at a later stage.

As shown in Figure 1, *Project management plan* (1), *Work performance information* (5), *Organizational process assets* (7), *Change requests* (10), *Work performance data* (15), *Project management plan updates* (39), *Project document updates* (40), and *Organizational process asset updates* (43) fell at the center of the PMBOK network, suggesting that these eight inputs and outputs may be core to project control. In fact, all the processes of the PMBOK network (8, 11, 16, 17, 21, 23, 29, 32, 34, 37, and 38) gravitate around these core inputs and outputs. Similarly, as shown in Figure 2, the process *Take corrective action* (31) and the inputs *Stage plan* (1) and *Risk register* (12) are at the center of the PRINCE2 network and can thus be considered as core elements to project control. The other seven project control processes (8, 13, 16, 20, 24, 27, and 30) are positioned not so far from the center of the PRINCE2 network.

Figure 3 shows that the AACE network can be divided into several groups: a singleton consisting of the *Project control plan implementation* (8) process falling at the center of the AACE model and considered as a core process to project control; closest to the singleton, a group of three core sub-processes, namely *Project performance assessment* (11), *Forecasting* (12), and *Change management* (13), which are part of the *Project control performance assessment* process; a group of five inputs and outputs (15, 19, 47, 59, and 88) that gravitate around the core sub-processes listed above; a group of six sub-processes located not so far from the center and composed of the following sub-processes: *Project scope and execution strategy development* (1), *Resource planning* (4), *Procurement planning* (7), *Project cost accounting* (9), *Progress and performance measurement* (10), and *Project historical database management* (14); and at the periphery of the network, two distinct groups, each composed of two sub-processes belonging to the *Project planning and control* process: a group made up of the *Schedule planning and development* (2) and the *Cost estimating and budgeting* (3) sub-processes, and another group that includes the *Value analysis and engineering* (5) and the *Risk management* (6) sub-processes.

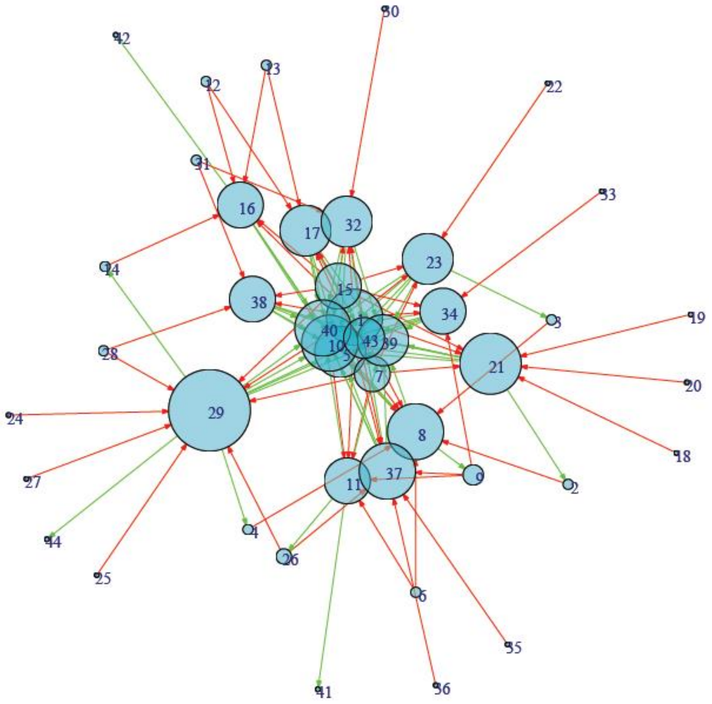

Fig. 1. PMBOK network

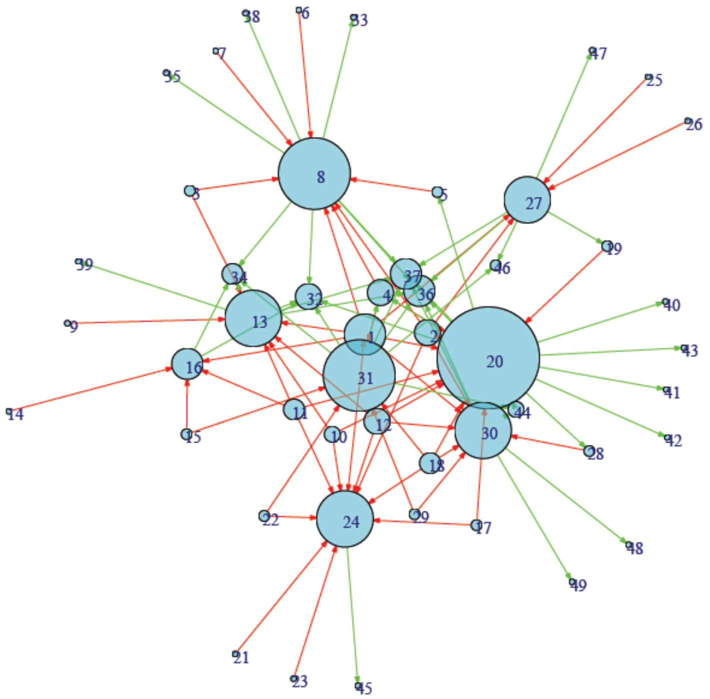

Fig. 2. PRINCE2 network

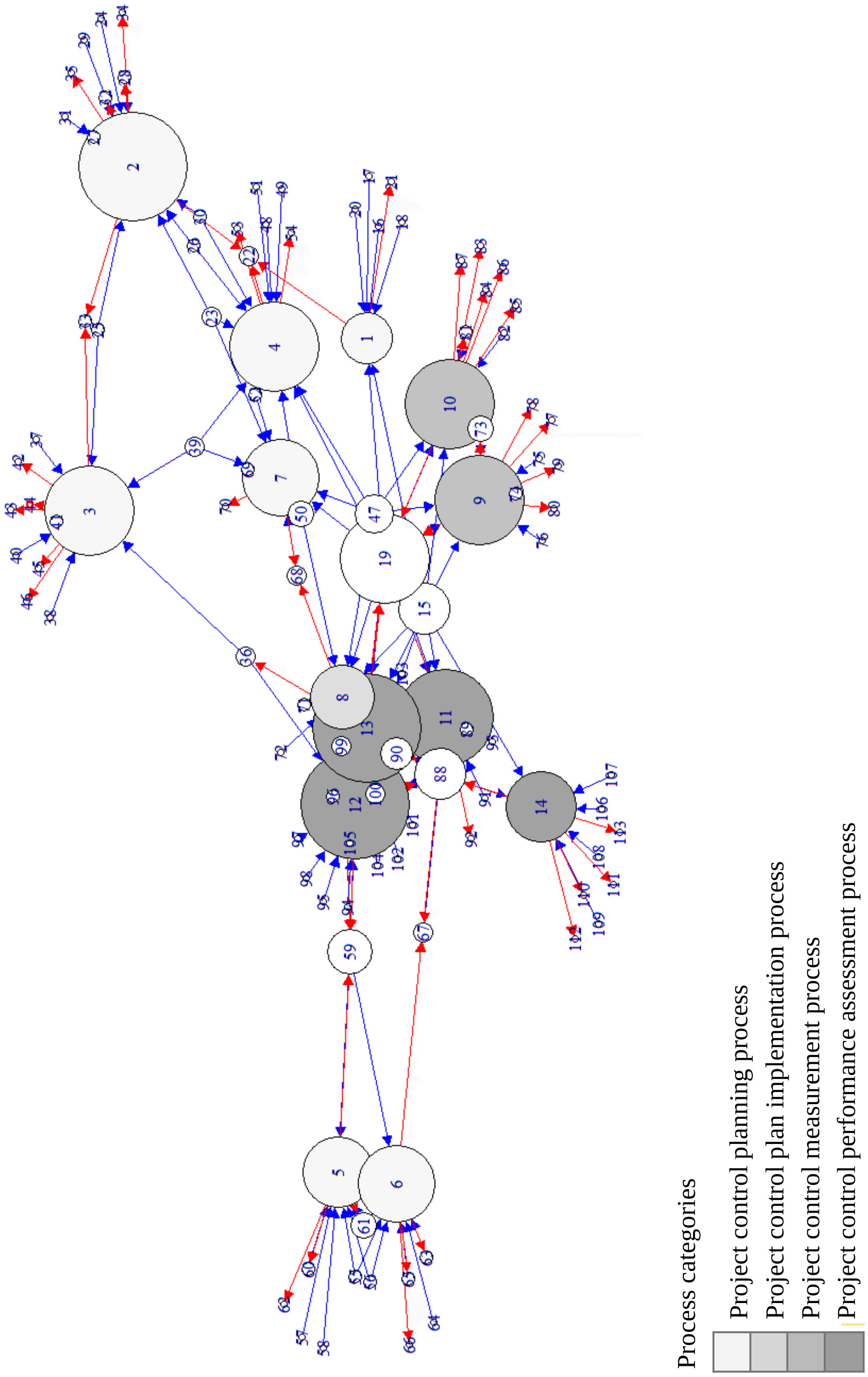

Fig. 3. AACE network

4.2 Centrality indices

Tables 7, 8, and 9 in Appendix B show the centrality metrics for the PMBOK, the PRINCE2, and the AACE networks, respectively. Higher numbers indicate that an item is more central to the network. Highest values within each centrality index are indicated in bold type. Values shown in the three tables in Appendix B are normalized values.

The indices of in-degree centrality and out-degree centrality for the PMBOK network support the finding that *Project management plan* (1), *Work performance information* (5), *Organizational process assets* (7), *Change requests* (10), *Work performance data* (15), *Project management plan updates* (39), *Project document updates* (40), and *Organizational process assets updates* (43) are central inputs and outputs to this network. Other PMBOK items with high in-degree and/or out-degree were the *Monitor and control project work* (8) and the *Control quality* (29) processes. Similarly, for the PRINCE2 network, the indices of in-degree and out-degree centrality also support the results of Section 4.1. The *Stage plan* (1) input as well as the *Review the stage status* (20) and the *Report highlights* (24) processes were the items with the highest in-degree and/or out-degree centrality. On the other hand, as shown in Table 9 in Appendix B, none of the AACE network vertices has a high in-degree or a high out-degree centrality value. All the processes, sub-processes, inputs, and outputs of the AACE framework can thus be considered as self-reliant entities, reducing the complexity of the overall AACE network in terms of network interactions.

To achieve further understanding of the positions of individual vertex and determine the key processes, the betweenness values are analyzed. The results show that *Monitor and control project work* (8), *Change requests* (10), *Perform integrated change control* (11), *Approved change requests* (26), and *Control quality* (29) all have higher betweenness in the PMBOK network model, illustrating that these processes, inputs, and outputs can exert substantial stress on information flow. As highlighted by Xue et al. [20], through the information flow, the items with higher betweenness possess considerable power in the network, because of their extensive potential to control the information flow. These items thus play key roles in the network. Similarly, we found that *Review the stage status* (20) is an important process that builds connections between processes, inputs, and outputs in the PRINCE2 network. Also, although they do not have strong immediate impacts on the others (low out-degree), *Forecasting* (12), *Change management* (13), *Historical Project Information* (19), and *Planning Information* (59) play the important role of hubs in connecting the processes, inputs, and outputs across the AACE network.

Finally, none of the vertices has a high closeness value in the three networks.

In order to classify project control processes within each standard, a scatter graph can be constructed to represent the values of out-degree versus in-degree centrality, from which the vertex types can be allocated to four categories ([23],[24]):

1) vertices with relatively low out-degree centrality and relatively low in-degree centrality, classified as autonomous;
2) vertices with relatively low out-degree centrality but relatively high in-degree centrality, classified as dependent;
3) influential vertices that have relatively high out-degree centrality but low in-degree centrality, indicating their crucial roles in influencing the network; and
4) linkage vertices, which have relatively high out-degree and in-degree centrality.

Influential and linkage vertices are significant vertices given their multiple roles in influencing network interactions [24]. Cancelling, delaying, or significantly altering any one of the linkage or influential processes can have a significant impact on many other processes in the network [23]. The out-degree versus in-degree centralities of each process, input, and output of the PBBOK network are plotted in Figure 4. Most of the PMBOK processes, inputs, and outputs can be classified as autonomous, since they have relatively low in-degree and out-degree centrality values. However, *Work performance information* (5), *Monitor and control project work* (8), *Change requests* (10), *Project management plan updates* (39), *Project documents updates* (40), and *Organizational process assets updates* (43) can be classified as dependent, since they have relatively low out-degree centrality but relatively high in-degree centrality. These items, which are predominantly outputs, can be thus greatly affected by other vertices in a direct way with their high in-degree values. Also, *Project management plan* (1), *Organizational process assets* (7), and *Work performance data* (15) can be classified as independent or influential, since they have relatively high out-degree centrality but relatively low in-degree centrality. These project control inputs exert strong direct influences on other vertices but receive no impact from the others. Finally, the process of *Control quality* (29) can be classified as a linkage or transmitter project control vertex, since it has relatively high out-degree and in-degree centralities. Given their key function in influencing network interactions, influential and linkage vertices play a primary role in the project control network. The complexity of the entire network after removing these key vertices can be greatly increased. Decision makers should thus in particular focus attention on these processes.

Similarly, for the PRINCE2 network, the out-degree versus in-degree centralities of each process, input and output are plotted in Figure 5. In terms of the vertex type, most of the vertices in the PRINCE2 network are ordinary or autonomous vertices, whereas three of them (24, 1, and 20) increase the complexity of the network. With its high in-degree value, the *Report highlights* (24) process can be classified as a dependent process, meaning that this process is directly affected by other processes, inputs or outputs. Also, the *Stage plan* (1) input is the vertex with the highest out-degree value, so this independent or influential input has the strongest direct impact on the other vertices in the PRINCE2 network. Another important vertex that has great potential to generate more impact is the *Review the stage status* (20) process because it has relatively high out-degree and in-degree centralities. This linkage process leads to the complexity of the entire PRINCE2 network as well. For the AACE network, recall that all the project control processes, sub-processes, inputs, and outputs are autonomous, since none of the vertices has high in-degree or out-degree centrality values (see Table 9 in Appendix B). The AACE project control network can thus be seen as a relatively less complex network in terms of process interactions, while the presence of influential and linkage vertices in both the PMBOK and PRINCE2 networks significantly leads to the overall complexity of these two networks.

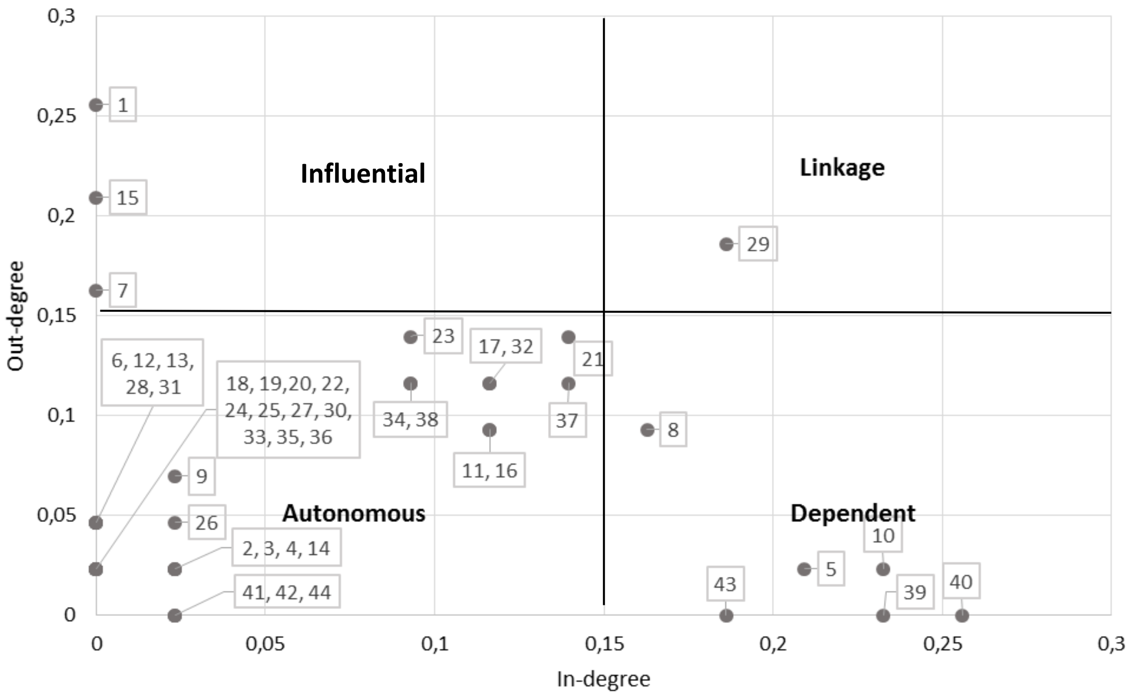

Fig. 4. PMBOK: out-degree versus in-degree centrality diagram

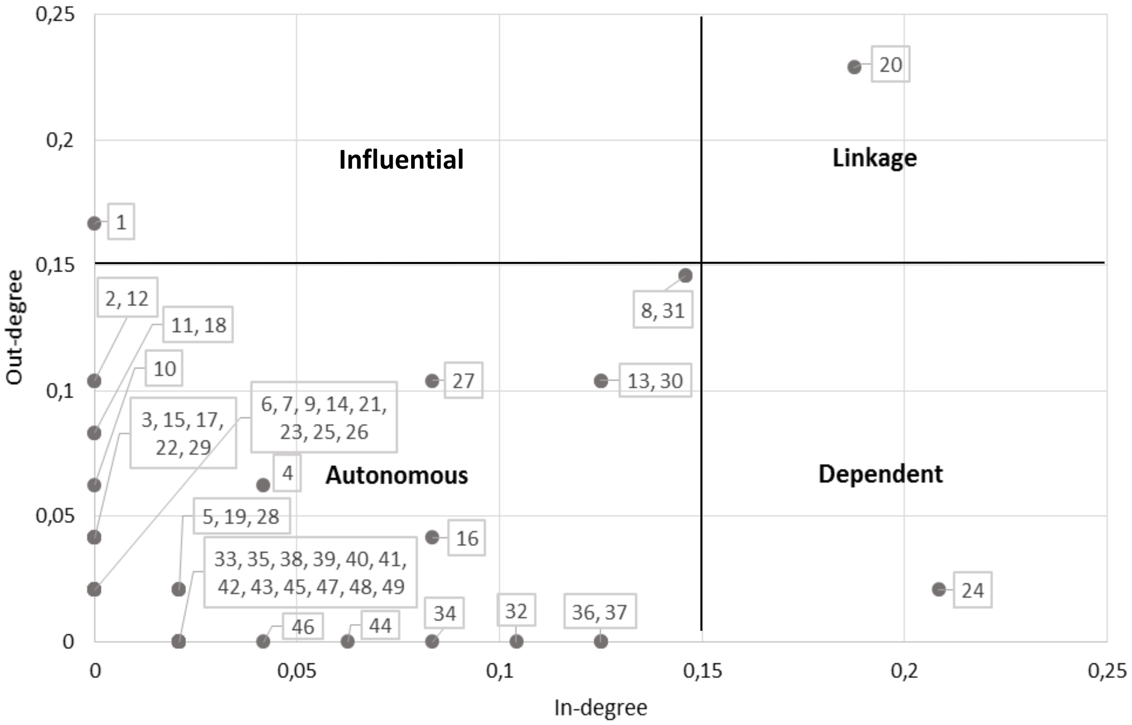

Fig. 5. PRINCE2: out-degree versus in-degree centrality diagram

5. Conclusion

Through network analysis, this paper examined the three standards of PMBOK, PRINCE2, and AACE for the control of projects. The findings showed that several processes, inputs, and outputs are central to project control. In particular, in both the PMBOK network and the PRINCE2 network, key vertices play different roles, such as linking and influential roles, and should be prioritized.

Linkage vertices are special vertices that have high out-degree values. Meanwhile, they are greatly affected by other vertices in a direct way with high in-degree values, indicating that these vertices are in the sensitive locations of the network and significantly lead to the overall network complexity [24]. For example, the *Control quality* (29) process was identified as a linkage process that leads the project control function in the PMBOK network. This finding supports research suggesting that quality is central to project control ([34],[35]). Similarly, the *Review the stage status* (20) process was identified as a linkage vertex in the PRINCE2 network. In addition, these two linkage processes have a high betweenness centrality, meaning that these processes should be regarded as significant channels in the network to gain access to information. Linkage processes are the most difficult processes to manage, since they depend on many other processes, while at the same time many other processes depend on them. Decision makers should thus pay particular attention to these processes.

The study also identified several influential vertices of project control. Influential or independent vertices have higher impacts on other vertices (high out-degree) compared with the impacts they receive (low in-degree). Interestingly, these vertices relate primarily to inputs throughout each network. In the PMBOK network, three influential inputs of project control were identified: *Project management plan* (1), *Organizational process assets* (7), and *Work performance data* (15). Similarly, the *Stage plan* (1) input was identified as highly central to project control and highly influential in the

PRINCE2 network. These inputs have direct impacts on a large number of vertices, leading to the complexity of the entire network, and should thus be given particular attention by project managers.

In contrast with both the PMBOK and PRINCE2 networks, it is worth noting that all the vertices in the AACE network were identified as autonomous with relatively low out-degree centrality and relatively low in-degree centrality, suggesting that none of the AACE vertices need specific attention. However, when analysing vertices with high betweenness centrality, we found that *Forecasting* (12), *Change management* (13), *Historical Project Information* (19), and *Planning Information* (59) are important hubs in the AACE network that build connections between vertices and consequently lead to impact propagation. These processes, inputs, and outputs must therefore be properly tracked to reduce the complexity of the network.

This study was limited to the analysis of the PMBOK, the PRINCE2, and the AACE framework project control processes. The use of network analysis in analysing other standards, such as PMI Foundational Standards, PMI Practice Standards and Frameworks, PMI Standards Extensions, ISO 1006, P3M3, Australian Institute of Project Management, HERMES, and Information Technology Infrastructure Library, and at additional phases of a project's life cycle (e.g., initiation, planning, execution, and closure) will enable a broad comparison between different standards at different phases.

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Appendix A. Inputs and outputs of project control processes

A.1. Detailed inputs and outputs of the PMBOK project control processes

Table 4. PMBOK project control processes: inputs (I) and outputs (O)

Processes	(1) Project management plan	(2) Schedule forecasts	(3) Cost forecasts	(4) Validated changes	(5) Work performance information	(6) Enterprise environmental factors	(7) Organizational process assets	(9) Work performance reports	(10) Change requests	(12) Requirements documentation	(13) Requirements traceability matrix	(14) Verified deliverables	(15) Work performance data	(18) Project schedule	(19) Project calendars	(20) Schedule data	(22) Project funding requirements	(24) Quality metrics	(25) Quality checklists	(26) Approved change requests	(27) Deliverables	(28) Project documents	(30) Project communications	(31) Issue log	(33) Risk register	(35) Procurement documents	(36) Agreements	(39) Project management plan updates	(40) Project documents updates	(41) Change log	(42) Accepted deliverables	(43) Organizational process assets updates	(44) Quality control measurements
(8) Monitor and control project work	I	I	I	I	I	I	I	O	O																			O	O				
(11) Perform integrated change control	I					I	I	I	I											O								O	O	O			
(16) Validate scope	I				O				O	I	I	I	I																O		O		
(17) Control scope	I				O		I		O	I	I		I															O	O			O	
(21) Control schedule	I	O			O		I		O				I	I	I	I												O	O			O	
(23) Control costs	I		O		O		I		O				I				I											O	O			O	
(29) Control quality	I			O	O		I		O			O	I					I	I	I	I	I						O	O			O	O
(32) Control communications	I				O		I		O				I										I	I				O	O			O	
(34) Control risks	I				O			I	O				I												I			O	O			O	
(37) Control procurement	I				O			I	O				I							I						I	I	O	O			O	
(38) Control stakeholder engagement	I				O				O				I									I		I				O	O			O	

A.2. Detailed inputs and outputs of the PRINCE2 project control activities

Table 5. PRINCE2 project control activities: inputs (I) and outputs (O)

Activities	(1) Stage plan	(2) Project initiation documentation	(3) Team plan	(4) Corrective action	(5) New work package	(6) Stage authorization	(7) Exception plan approved	(9) Work package(s)	(10) Checkpoint report(s)	(11) Quality register	(12) Risk register	(14) Completed work package	(15) Configuration item records	(17) Product status account	(18) Issue register	(19) Project board advice	(21) Lessons log	(22) Daily log	(23) Highlight report (previous period)	(25) New risk	(26) New issue	(28) Tolerance threat	(29) Issue report	(32) Update stage plan	(33) Create work package(s)	(34) Update configurations item records	(35) Update quality register	(36) Update risk register	(37) Update issue register	(38) Authority to deliver a work package	(39) Update work package	(40) Project and approaching	(41) Stage boundary approaching	(42) Request for advice	(43) Update lessons log	(44) Update issue report	(45) Create highlight report (current period)	(46) Update daily log	(47) Create issue report	(48) Create exception report	(49) Exception raised
(8) Authorize a work package	I	I	I	I	I	I	I																	O	O	O	O	O	O	O											
(13) Review work packages status	I		I					I	I	I	I													O		O		O	O		O										
(16) Receive complete work packages	I									I		I	I											O		O															
(20) Review the stage status	I	I		I O	O				I	I	I			I	I	I						O		O				O	O			O	O	O	O	O					
(24) Report highlights	I	I							I	I	I			I	I		I	I	I																		O				
(27) Capture and examine issues & risks	I	I														O				I	I							O	O									O	O		
(30) Escalate issues and risks	I	I									I				I							I	I					O	O							O				O	O
(31) Take corrective action	I			I O							I		I		I			I					I	O		O		O	O							O		O			

A.3. Detailed inputs and outputs of the AACE project control processes and sub-processes

Table 6. AACE project control processes and sub-processes: inputs (I) and outputs (O)

Inputs and outputs	(8) Project scope and execution strategy development	(9) Schedule planning and development	(10) Cost estimating and budgeting	(11) Resource planning	(12) Value analysis and engineering	(13) Risk management	(14) Procurement planning	(15) Project control plan implementation	(16) Project cost accounting	(17) Progress and performance measurement	(18) Project performance assessment	(19) Forecasting	(20) Change management	(21) Project historical database management
(15) Project implementation basis	I							I	I	I	I	I	I	I
(16) Asset alternatives	I													
(17) Change information	I													
(18) Defining deliverables	I													
(19) Historical project information	I			I			I	I	I-O	I-O	I-O	I-O	I-O	
(20) Planning process plans	I													
(21) Basis for planning	O													
(22) Basis for asset planning	O	O		O										
(23) Project planning basis		I		I			I							
(24) Work breakdown structure (WBS), work packages, and execution strategy		I												
(25) Technical deliverables		I	I											
(26) Asset alternative scope		I		I										
(27) Historical schedule information		I-O												
(28) Trends, deviations, and changes		I-O												
(29) Estimated costs		I												
(30) Resource quantities		I		I										
(31) Information from project planning		I												
(32) Schedule submittals		I-O												
(33) Refined scope development		O	O											
(34) Information for project planning		O												
(35) Basis for schedule performance measurement and assessment		O												
(36) Scope definition			I									I	O	
(37) Schedule information			I											
(38) WBS			I											
(39) Chart of accounts			I	I			I							
(40) Historical cost information			I											
(41) Estimate information			I-O											
(42) Cost control baseline			O											
(43) Resource requirements			O											
(44) Cost information for analyses			O											
(45) Estimate basis			O											
(46) Refined plan and schedule			O											
(47) Changes				I			I	I	I	I	I			
(48) Resource expenditure information				I										

Inputs and outputs	(8) Project scope and execution strategy development	(9) Schedule planning and development	(10) Cost estimating and budgeting	(11) Resource planning	(12) Value analysis and engineering	(13) Risk management	(14) Procurement planning	(15) Project control plan implementation	(16) Project cost accounting	(17) Progress and performance measurement	(18) Project performance assessment	(19) Forecasting	(20) Change management	(21) Project historical database management
(49) Organizational breakdown structure (OBS)				I										
(50) Execution strategy				I			I-O	I						
(51) Societal values and performance considerations				I										
(52) Information for analysis				I			I							
(53) Resource quantity availability and limitations				O										
(54) Basis for project control plans and plan implementation				O										
(55) Strategic asset requirements and project implementation basis					I	I								
(56) Asset or project scope					I	I								
(57) Asset or project technical information					I									
(58) Customer requirements					I									
(59) Planning information					I-O	I		I-O				I-O		
(60) Cost information					I-O									
(61) Historical information					I-O	I-O								
(62) Value study report					O									
(63) Cost, schedule, and resource information						I-O								
(64) Risk performance assessment						I								
(65) Change information and contingency management						I-O								
(66) Planning basis information						O								
(67) Risk management plan						O					I-O			
(68) Basis for project control							I-O	O						
(69) Estimate and schedule information							I-O							
(70) Contract requirements for project control							O							
(71) WBS, OBS, and work packages								I-O						
(72) Validation metrics								I						
(73) Project control plan and control accounts									I-O	I-O				
(74) Progress measurement plans									I-O					
(75) Work progress									I					
(76) Charges to project accounts									I					
(77) Corrections to charges									O					
(78) Cost information for financing									O					
(79) Cost information for capitalization									O					
(80) Cost information for control									O					
(81) Project cost accounting plans										I-O				
(82) Work, resource, and process performance										I				
(83) Corrections to measurement basis										O				
(84) Information for enterprise resource planning										O				
(85) Measurement information for project cost accounting										O				
(86) Measurement information for performance assessment										O				
(87) Status information for change management										O				
(88) Project control plan											I-O	I-O	I-O	I-O
(89) Performance measurement plans											I-O			
(90) Project control basis											I-O	I-O	O	

Inputs and outputs	(8) Project scope and execution strategy development	(9) Schedule planning and development	(10) Cost estimating and budgeting	(11) Resource planning	(12) Value analysis and engineering	(13) Risk management	(14) Procurement planning	(15) Project control plan implementation	(16) Project cost accounting	(17) Progress and performance measurement	(18) Project performance assessment	(19) Forecasting	(20) Change management	(21) Project historical database management
(91) Performance measures and observations											I			
(92) Information for forecasting											O			
(93) Information for project change management											O			
(94) Scope of changes												I		
(95) Physical progress												I		
(96) Trends												I	O	
(97) Corrective actions												I		
(98) Approved scope												I		
(99) Corrective action alternatives												O	I-O	
(100) Alternative forecasts												O	I-O	
(101) Deviation, notices, and change requests													I	
(102) Variances													I	
(103) Risk management information													I	
(104) Procurement information													I	
(105) Selected corrective actions and approved scope													O	
(106) Control baseline data														I
(107) Actual performance data														I
(108) Performance and methods and tools experiences														I
(109) Project system and external information														I
(110) Planning reference data														O
(111) Plan validation data														O
(112) Data to support methods and tools development														O
(113) Information for project system management														O

Appendix B. Centrality measures

B.1. PMBOK network centrality measures

Table 7. Centrality measures for the PMBOK network

No.	Processes, inputs, and outputs	In-degree	Out-degree	Betweenness	Closeness
1	Project management plan	0	**0.256**	0	0.052
2	Schedule forecasts	0.023	0.023	0.008	0.037
3	Cost forecasts	0.023	0.023	0.004	0.037
4	Validated changes	0.023	0.023	0.013	0.036
5	Work performance information	**0.209**	0.023	0.085	0.035
6	Enterprise environmental factors	0	0.047	0	0.037
7	Organizational process assets	0	**0.163**	0	0.049
8	Monitor and control project work	**0.163**	0.093	**0.161**	0.036
9	Work performance reports	0.023	0.070	0.094	0.036

No.	Processes, inputs, and outputs	In-degree	Out-degree	Betweenness	Closeness
10	Change requests	**0.233**	0.023	**0.248**	0.036
11	Perform integrated change control	0.116	0.093	**0.282**	0.036
12	Requirements documentation	0	0.047	0	0.038
13	Requirements traceability matrix	0	0.047	0	0.038
14	Verified deliverables	0.023	0.023	0.071	0.036
15	Work performance data	0.000	**0.209**	0	0.051
16	Validate scope	0.116	0.093	0.074	0.036
17	Control scope	0.116	0.116	0.023	0.037
18	Project schedule	0	0.023	0	0.039
19	Project calendars	0	0.023	0	0.039
20	Schedule data	0	0.023	0	0.039
21	Control schedule	0.140	0.140	0.069	0.039
22	Project funding requirements	0.000	0.023	0	0.039
23	Control costs	0.093	0.140	0.027	0.039
24	Quality metrics	0	0.023	0	0.037
25	Quality checklists	0	0.023	0	0.037
26	Approved change requests	0.023	0.047	**0.210**	0.036
27	Deliverables	0	0.023	0	0.037
28	Project documents	0	0.047	0	0.039
29	Control quality	**0.186**	**0.186**	**0.254**	0.037
30	Project communications	0	0.023	0	0.038
31	Issue log	0	0.047	0	0.039
32	Control communications	0.116	0.116	0.033	0.037
33	Risk register	0	0.023	0	0.037
34	Control risks	0.093	0.116	0.030	0.036
35	Procurement documents	0	0.023	0	0.037
36	Agreements	0	0.023	0	0.037
37	Control procurements	0.140	0.116	0.060	0.036
38	Control stakeholder engagement	0.093	0.116	0.018	0.037
39	Project management plan updates	**0.233**	0	0	0.023
40	Project documents updates	**0.256**	0	0	0.023
41	Change log	0.023	0	0	0.023
42	Accepted deliverables	0.023	0	0	0.023
43	Organizational process assets updates	**0.186**	0	0	0.023
44	Quality control measurements	0.023	0	0	0.023

B.2. PRINCE2 network centrality measures

Table 8. Centrality measures for the PRINCE2 network

No.	Processes, inputs, and outputs	In-degree	Out-degree	Betweenness	Closeness
1	Stage plan	0	**0.167**	0	0.051
2	Project initiation documentation	0	0.104	0	0.044
3	Team plan	0	0.042	0	0.026
4	Corrective action	0.042	0.063	0.082	0.035
5	New work package	0.021	0.021	0.018	0.024
6	Stage authorization	0	0.021	0	0.024
7	Exception plan approved	0	0.021	0	0.024
8	Authorize a work package	0.146	0.146	0.076	0.024
9	Work package(s)	0	0.021	0	0.023
10	Checkpoint report(s)	0	0.063	0	0.042
11	Quality register	0	0.083	0	0.044
12	Risk register	0	0.104	0	0.042
13	Review work packages status	0.125	0.104	0.016	0.023
14	Completed work package	0	0.021	0	0.022
15	Configuration item records	0	0.042	0	0.037
16	Receive complete work packages	0.083	0.042	0.004	0.021
17	Product status account	0	0.042	0	0.039
18	Issue register	0	0.083	0	0.039
19	Project board advice	0.021	0.021	0.051	0.036
20	Review the stage status	**0.188**	**0.229**	**0.190**	0.035
21	Lessons log	0	0.021	0	0.021
22	Daily log	0	0.042	0	0.038
23	Highlight report (previous period)	0	0.021	0	0.021
24	Report highlights	**0.208**	0.021	0.009	0.021
25	New risk	0	0.021	0	0.039
26	New issue	0	0.021	0	0.039
27	Capture and examine issues & risks	0.083	0.104	0.048	0.038
28	Tolerance threat	0.021	0.021	0.032	0.023
29	Issue report	0	0.042	0	0.036
30	Escalate issues and risks	0.125	0.104	0.039	0.023
31	Take corrective action	0.146	0.146	0.070	0.035
32	Update stage plan	0.104	0	0	0.020
33	Create work package(s)	0.021	0	0	0.020
34	Update configurations item records	0.083	0	0	0.020
35	Update quality register	0.021	0	0	0.020
36	Update risk register	0.125	0	0	0.020
37	Update issue register	0.125	0	0	0.020
38	Authority to deliver a work package	0.021	0	0	0.020
39	Update work package	0.021	0	0	0.020
40	Project and approaching	0.021	0	0	0.020
41	Stage boundary approaching	0.021	0	0	0.020
42	Request for advice	0.021	0	0	0.020
43	Update lessons log	0.021	0	0	0.020
44	Update issue report	0.063	0	0	0.020
45	Create highlight report (current period)	0.021	0	0	0.020
46	Update daily log	0.042	0	0	0.020

No.	Processes, inputs, and outputs	In-degree	Out-degree	Betweenness	Closeness
47	Create issue report	0.021	0	0	0.020
48	Create exception report	0.021	0	0	0.020
49	Exception raised	0.021	0	0	0.020

B.3. AACE network centrality measures

Table 9. Centrality measures for the AACE network

No.	Processes, inputs, and outputs	In-degree	Out-degree	Betweenness	Closeness
1	Project scope and execution strategy development	0.054	0.018	0.015	0.009
2	Schedule planning and development	0.089	0.063	0.010	0.009
3	Cost estimating and budgeting	0.063	0.063	0.071	0.009
4	Resource planning	0.098	0.027	0.026	0.009
5	Value analysis and engineering	0.063	0.036	0.069	0.019
6	Risk management	0.063	0.045	0.077	0.019
7	Procurement planning	0.071	0.036	0.076	0.019
8	Project control plan implementation	0.063	0.027	0.106	0.019
9	Project cost accounting	0.063	0.063	0.083	0.020
10	Progress and performance measurement	0.054	0.071	0.082	0.020
11	Project performance assessment	0.071	0.063	0.120	0.020
12	Forecasting	0.098	0.054	**0.227**	0.020
13	Change management	0.080	0.071	**0.164**	0.020
14	Project historical database management	0.054	0.045	0.075	0.019
15	Project implementation basis	0	0.071	0	0.020
16	Asset alternatives	0	0.009	0	0.009
17	Change information	0	0.009	0	0.009
18	Defining deliverables	0	0.009	0	0.009
19	Historical project information	0.045	0.080	**0.282**	0.020
20	Planning process plans	0	0.009	0	0.009
21	Basis for planning	0.009	0	0	0.009
22	Basis for asset planning	0.027	0	0	0.009
23	Project planning basis	0	0.027	0	0.022
24	WBS, work packages, and execution strategy	0	0.009	0	0.010
25	Technical deliverables	0	0.018	0	0.010
26	Asset alternative scope	0	0.018	0	0.010
27	Historical schedule information	0.009	0.009	0	0.009
28	Trends, deviations, and changes	0.009	0.009	0	0.009
29	Estimated costs	0	0.009	0	0.010
30	Resource quantities	0	0.018	0	0.010
31	Information from project planning	0	0.009	0	0.010
32	Schedule submittals	0.009	0.009	0	0.009
33	Refined scope development	0.018	0	0	0.009
34	Information for project planning	0.009	0	0	0.009
35	Basis for schedule performance measurement and assessment	0.009	0	0	0.009
36	Scope definition	0.009	0.018	0.074	0.019
37	Schedule information	0	0.009	0	0.010
38	WBS	0	0.009	0	0.010
39	Chart of accounts	0	0.027	0	0.019
40	Historical cost information	0	0.009	0	0.010
41	Estimate information	0.009	0.009	0	0.009

No.	Processes, inputs, and outputs	In-degree	Out-degree	Betweenness	Closeness
42	Cost control baseline	0.009	0	0	0.009
43	Resource requirements	0.009	0	0	0.009
44	Cost information for analyses	0.009	0	0	0.009
45	Estimate basis	0.009	0	0	0.009
46	Refined plan and schedule	0.009	0	0	0.009
47	Changes	0	0.054	0	0.020
48	Resource expenditure information	0	0.009	0	0.009
49	OBS	0	0.009	0	0.009
50	Execution strategy	0.009	0.027	0.054	0.019
51	Societal values and performance considerations	0	0.009	0	0.009
52	Information for analysis	0	0.018	0	0.019
53	Resource quantity availability and limitations	0.009	0	0	0.009
54	Basis for project control plans and plan implementation	0.009	0	0	0.009
55	Strategic asset requirements and project implementation basis	0	0.018	0	0.019
56	Asset or project scope	0	0.018	0	0.019
57	Asset or project technical information	0	0.009	0	0.019
58	Customer requirements	0	0.009	0	0.019
59	Planning information	0.027	0.036	**0.184**	0.019
60	Cost information	0.009	0.009	0	0.019
61	Historical information	0.018	0.018	0.006	0.019
62	Value study report	0.009	0	0	0.009
63	Cost, schedule, and resource information	0.009	0.009	0	0.019
64	Risk performance assessment	0	0.009	0	0.019
65	Change information and contingency management	0.009	0.009	0	0.019
66	Planning basis information	0.009	0	0	0.009
67	Risk management plan	0.018	0.009	0.048	0.019
68	Basis for project control	0.018	0.009	0.005	0.019
69	Estimate and schedule information	0.009	0.009	0	0.019
70	Contract requirements for project control	0.009	0	0	0.009
71	WBS, OBS, and work packages	0.009	0.009	0	0.019
72	Validation metrics	0	0.009	0	0.019
73	Project control plan and control accounts	0.018	0.018	0.004	0.019
74	Progress measurement plans	0.009	0.009	0	0.019
75	Work progress	0	0.009	0	0.020
76	Charges to project accounts	0	0.009	0	0.020
77	Corrections to charges	0.009	0	0	0.009
78	Cost information for financing	0.009	0	0	0.009
79	Cost information for capitalization	0.009	0	0	0.009
80	Cost information for control	0.009	0	0	0.009
81	Project cost accounting plans	0.009	0.009	0	0.019
82	Work, resource, and process performance	0	0.009	0	0.020
83	Corrections to measurement basis	0.009	0	0	0.009
84	Information for enterprise resource planning	0.009	0	0	0.009
85	Measurement information for project cost accounting	0.009	0	0	0.009
86	Measurement information for performance assessment	0.009	0	0	0.009
87	Status information for change management	0.009	0	0	0.009
88	Project control plan	0.036	0.036	0.119	0.020
89	Performance measurement plans	0.009	0.009	0	0.019
90	Project control basis	0.027	0.018	0.010	0.019
91	Performance measures and observations	0	0.009	0	0.020

No.	Processes, inputs, and outputs	In-degree	Out-degree	Betweenness	Closeness
92	Information for forecasting	0.009	0	0	0.009
93	Information for project change management	0.009	0	0	0.009
94	Scope of changes	0	0.009	0	0.020
95	Physical progress	0	0.009	0	0.020
96	Trends	0.009	0.009	0.002	0.019
97	Corrective actions	0	0.009	0	0.020
98	Approved scope	0	0.009	0	0.020
99	Corrective action alternatives	0.018	0.009	0.011	0.019
100	Alternative forecasts	0.018	0.009	0.011	0.019
101	Deviation notices and change requests	0	0.009	0	0.020
102	Variances	0	0.009	0	0.020
103	Risk management information	0	0.009	0	0.020
104	Procurement information	0	0.009	0	0.020
105	Selected corrective actions and approved scope	0.009	0	0	0.009
106	Control baseline data	0	0.009	0	0.020
107	Actual performance data	0	0.009	0	0.020
108	Performance and methods and tools experiences	0	0.009	0	0.020
109	Project system and external information	0	0.009	0	0.020
110	Planning reference data	0.009	0	0	0.009
111	Plan validation data	0.009	0	0	0.009
112	Data to support methods and tools development	0.009	0	0	0.009
113	Information for project system management	0.009	0	0	0.009

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