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Research Article

Modeling and Simulation of Project Management through the PMBOK® Standard Using Complex Networks

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Discussion about project management, in both the academic literature and industry, is predominantly based on theories of control, many of which have been developed since the 1950s. However, issues arise when these ideas are applied unilaterally to all types of projects and in all contexts. In complex environments, management problems arise from assuming that results, predicted at the start of a project, can be sufficiently described and delivered as planned. Thus, once a project reaches a critical size, a calendar, and a certain level of ambiguity and interconnection, the analysis centered on control does not function adequately. Projects that involve complex situations can be described as adaptive complex systems, consistent in multiple interdependent dynamic components, multiple feedback processes, nonlinear relations, and management of hard data (process dynamics) and soft data (executive team dynamics). In this study, through a complex network, the dynamic structure of a project and its trajectories are simulated using inference processes. Finally, some numerical simulations are described, leading to a decision making tool that identifies critical processes, thereby obtaining better performance outcomes of projects.

1. Introduction

Projects have long been considered business practices of high value for organizations, with important results in general. Therefore, project management is considered a key factor for the success of projects and strategic objectives of companies [1]. In 1950, the social construct of *project management* was first introduced (in the United States Air Force). Its first proponent was Brigadier Bernard Schriever, who implemented the concept of concurrence, integrating all the elements of a project into a single program and budget, executed in parallel and not in sequence. Since then, specific techniques have arisen—histograms, chronograms, concepts of the life cycle of a project, and the work breakdown structure, which make up the knowledge base of the classic perspective of projects [2].

According to Padalkar and Gopinath [3], a significant part of the first studies on project management, which continued up to the 1980s, used conceptual or analytical methods. These methods focused on the optimization of scheduling based on the premise that project activities and their interrelations were fixed and measurable [4–8].

Subsequently, in the 1990s, new results of empirical experiments studying the success and failure of projects surfaced [9–22]. Defining the concepts of success and failure associated with projects and their management is not an easy task, and there is no consensus on their definition or measurement. According to Baccarini [10], there must be a distinction between the success of a project as measured by the fulfillment of the requirements of the end product, and the success of the project management as measured habitually in terms of time, costs, and quality [23].

The pursuit of the success/failure of projects has led to an expansion of research on organization contexts that are broader, behavioral, and interdisciplinary [9, 14, 17, 24–28]. This has promoted other research on such topics as contingencies, behavior, and governance in projects, interrelations between projects, decision making, and the perspective of complexity [2].

From the 1960s, a small deviation from the classic deterministic perspective started to emerge, in which nondeterministic processes began to be considered. This included criticism of PERT and the beta-distribution [29–31], and the treatment of project management as being not only deterministic [32]. The modeling of the uncertainty of project phenomena began to be considered as assumptions about attributes considered static broadened [33–39]. System dynamics began to be used for modeling the nonlinear effects of feedback loops in projects [40–43] and the modeling of projects under diffuse or probabilistic assumptions [44–48].

The dominant research focus has remained instrumentalist, with attempts to design models or methods of decision making with the goal of analyzing the performance of a project (e.g., the Project Management Body of Knowledge (PMBOK) standard from the Project Management Institute, which was founded in 1969 and its 5th edition was published in 2013).

The nondeterministic school of thought finds meaning in the weak theoretical nature of project management [1, 49–55].

From a brief exploration of literature, several attempts to model projects through assumptions related to complexity are found [56–61]. Several studies have theoretically discussed, defined, or provided constitutive elements of complexity [42, 50, 62–67, 67–73]. Other studies have done the same with regard to uncertainty [18, 60, 74–77].

In addition, the literature review provides evidence of the existence of several international organizations that have been expanding the body of knowledge of project management: ISO (21500), International Project Management Association, 1972, standard ICB 3.0, Association for Project Management, standard PRINCE2, Project Management Institute (PMI), 1969, PMBOK standard, International Centre for Complex Project Management, 2011, and New England Complex Systems Institute, amongst others.

For the purpose of this study and the evaluation of project management, the analysis is based on the PMBOK standard from the PMI, given its importance and international prevalence. It was chosen with the goal of describing an analytic structure of processes and as a tool for simulating complex networks used to evaluate project management nondeterministically.

1.1. Project Management as a Complex System. Complexity theory as applied to organizations [78] can also be applied to projects [42, 62]. All projects have attributes of interconnection, hierarchy, communication, control, and emergency, which are generally useful attributes for describing all types of systems [79]. In addition, most big and small projects exhibit characteristics of complex adaptive systems. They exhibit such characteristics as phase transitions, adaptability, and sensibility to initial conditions [79].

A complex project is a complex system made up of different elements interconnected to achieve an objective. Such a system can be described by a dynamic system, whose parts interact with each other and with their environment, and such interactions give rise to new properties that did not previously exist [80].

According to [79], the most important characteristics exhibited by complex projects, seen as complex adaptive systems, are as follows:

(i) Auto-organization*:* a project can suffer two types of perturbations—those of an exogenic nature (relating to changes of its environment) and those of an endogenous nature (relating to internal attribute changes that modify the relationships within the system) [81]. After a given perturbation, the project is reorganized until a new emerging structure is adopted, which can be fixed as long as no new environment or internal parameter changes occur.

(ii) Hierarchy: projects as systems might contain other systems—the members of the temporary executive organization of the project in turn belong to other subsystems. In addition, the structures of work breakdown form hierarchies for the execution of activities, and the project can be perceived from different levels depending on the interest of the observer and so on.

(iii) Nonlinearity: small perturbations cause effects in projects. The result of a small variation in the exogenous inputs or endogenous parameters can lead to considerable variations in the system (either immediately or in the future), contrasting a linear effect.

(iv) Adaptability: adaptive systems can reorder their internal structure without the intervention of an external agent. This property, which is the product of unconscious learning, increases the probability that the system survives turbulent and unstable environments.

The remainder of this article is structured in the following manner. In Section 2, the modeling of process dynamics is described based on the PMBOK standard, along with the creation of a complex network. Section 3 is dedicated to numerical simulation and the results obtained. Finally, Section 4 describes the conclusions.

2. Modeling of a Complex Network of Processes Based on the PMBOK Standard

This section describes a possible algorithm to model complex project management through the creation of a complex network, in which nodes are the different processes of the project, and edges are the exchanges of information between such.

2.1. Determination of Generalities. Research, such as [82], suggests an appropriate sequence to develop a project management plan based on the PMBOK and focused on network theory. This research analyzes the activities of a project from a classic and deterministic perspective, while the present work evaluates the behavior of project management from the perspective of complexity, describing a structure for analyzing processes as a model that evaluates the dynamics of connections through simulation in a complex network, and an analysis of the behavior of the characteristics of a complex project.

The methodological guide PMBOK, in its 5th edition (2013), describes five process groups and 10 knowledge areas that can be used to identify the relevant factors in arbitrary projects. The 10 knowledge areas are integration, scope, time, costs, quality, human resources, communications, risks, procurement, and stakeholders.

The five process groups are initiating, planning, executing, monitoring and controlling, and closing:

(i) *Initiating process group* includes processes that define a new project or phase of an existing one, helping establish the vision and requirements. In this group, there are two subprocesses.

(ii) *Planning process group* includes processes carried out to establish the scope of the plan, define and review the objectives, and develop an action plan to reach such objectives. In this group, there are 24 subprocesses.

(iii) *Executing process group* includes processes targeted at completing the work defined in planning, with the goal of satisfying the requirements of such. In this group, there are eight subprocesses.

(iv) *Monitoring and controlling process group* includes processes required to trace, analyze, and direct the progress and performance of the project, making necessary changes to it. In this group, there are 11 subprocesses.

(v) *Closing process group* includes processes required to close a phase of the project or its entirety. In this group, there are two subprocesses.

2.2. Definition of the Analytic Structure of Processes. To model and simulate the analytic structure of processes, the following steps are defined.

(i) Describe the subprocesses in terms of the flow of information.

(ii) Define the model of connections between subprocesses.

(iii) Determine parameters of the simulation.

(iv) Present and discuss the results of the simulation of a complex network of subprocesses.

3. Simulation of the Complex Network of Processes or Subprocesses

In this section, subprocesses and the connections between them are described in terms of the flow of information. In addition, the parameters of the simulation are determined and the results of the simulations displayed.

3.1. Description of Subprocesses in terms of Information Flow. (a) There are 26 initiating and planning subprocesses. They are the following: develop the project charter (see the example in Figure 1), identify stakeholders, develop project management plan, plan scope management, collect requirements, define scope, create the EDT/WBS, plan schedule management, define activities, sequence the activities, estimate activity resources, estimate activity durations, develop schedule, plan cost management, estimate costs, determine budget, plan quality management, plan human resources management, plan communication management, plan risk management, identify risks, perform qualitative analysis, perform quantitative analysis, plan risk response, plan procurement management, and plan stakeholder management.

(b) There are 8 subprocesses in the executing process: direct and manage the work of the project (see an example in Figure 2), perform quality assurance, acquire project team, develop project team, manage project team, manage communications, conduct procurements, and manage stakeholder engagement.

(c) There are 11 subprocesses in the process of monitoring and controlling: monitoring and controlling project work, performing integrated change control, validating scope, controlling scope, controlling the schedule, controlling costs, controlling quality, controlling communications, controlling risks, controlling procurements, and controlling stakeholder engagement.

(d) There are two subprocesses in the closing process: close the project or phase and close the project or phase (procurements).

(e) Three new subprocesses are added (extending the PMBOK standard), and they are repository (contains the information of the project), exogenous (effects of the known environment variables), and novelties (effects of unknown variables).

As a result, 49 nodes are identified: 25 belonging to the subprocess of planning, 8 to the subprocess of execution, 11 to the subprocess of monitoring and controlling, 2 to the subprocess of closing, and 3 additional ones. In order to execute the activities of each subprocess, it is necessary for information to flow from other subprocesses and for new information to be generated, which flows into other subprocesses.

3.2. Connection Model between Subprocesses. Based on the subprocesses defined previously, relationships between these processes are defined as connections in the network, which are temporal. In addition, each subprocess is a node in the complex network.

The connections, or links, are established by the optimal relationship principle, which finds efficiencies between nodes and eliminates redundancies (i.e., not revisiting a node if it has been updated already). In order to elucidate this concept, consider the node "develop the project charter."

(i) The nodes that we label as sources are those that can send the following information: (1) exogenous node and/or (2) qualitative analysis of risk node.

(ii) The nodes that we label as outputs are those that can receive information from (1) repository node, (2) developing project management plan, (3) planning scope management, (4) collecting requirements,

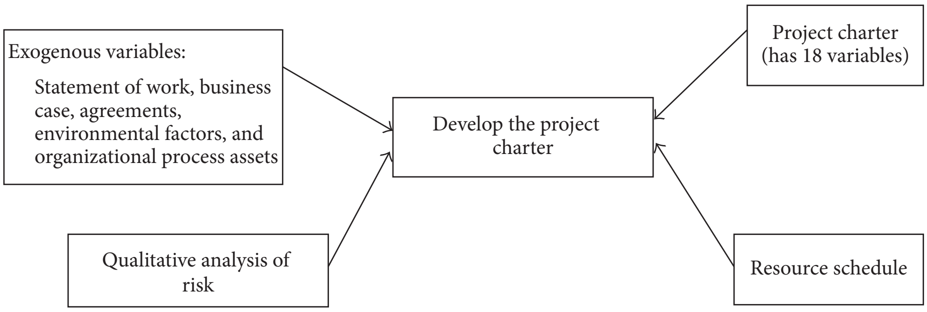

Figure 1: Area of knowledge of integration, initiation process, and development of the project charter subprocess (based on PMBOK).

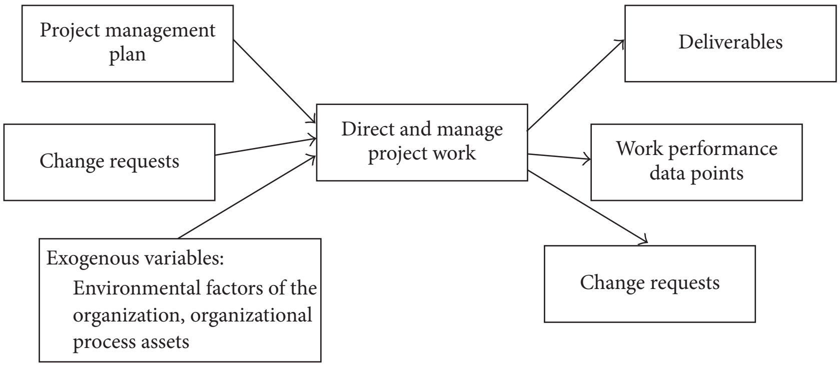

Figure 2: Area of knowledge of integration, executing process, and directing and management of project work subprocess (based on PMBOK).

(5) defining scope, (6) planning schedule management, (7) planning cost management, (8) planning risk management, and/or (9) identifying stakeholders.

When the node "develop the project charter" is activated by a source node, it processes the input information and then activates the output processes. These output processes in turn can activate other processes with which they have some relationship within the complex network. Thus, not only output node connections but also the secondary node sequence of the outputs is modeled.

3.3. Determining the Parameters of the Simulation. The conditions and hypothesis established in this subsection are the following, corresponding to the PMBOK standard.

(i) The 49 subprocesses are determined based on PMBOK.

(ii) It is assumed that there exists perfect information of the project in the planning phase and that the phases of executing, monitoring and controlling, and closing are carried out.

(iii) The project considered is arbitrary, and the simulation attempts to evaluate the behavior of the project management are as defined by PMBOK.

(iv) Each node is identified by a number, in order to simplify the simulation process.

(v) Through color labeling, the dynamics of each node and connection can be established (see [83]):

  (a) green node, idle state
  (b) blue node, sending information state
  (c) yellow node, receiving information state
  (d) red node, processing information state
  (e) purple connection, active state sending information
  (f) black connection, inactive state

(vi) The processing time of each node and the delay of the connection between two nodes are determined by a discrete uniform distribution that takes integer values between 1 and 11. This is done to exemplify the process, without setting the values to specific real cases, and these values are in the time units of the project.

(vii) Connections are simulated concurrently. This takes place whenever a source node transfers information to several sinks, and when the sink node has several outputs (see [84–86]).

(viii) The phases of project management are simulated in the following sequence: planning, executing, monitoring and controlling, and closing. This is also based on the PMBOK standard.

To illustrate the above, the subprocess "develop the project charter" is taken as an example, using a numerical identifier to simplify the simulation process, as follows: source nodes: exogenous (1) and qualitative analysis of risk

Table 1: Defining the connections of the network.

Source	Sink	Output
1; 38;	3;	0; 4; 9; 10; 11; 15; 22; 36; 46;

Table 2: Next generation of information connections between the nodes in the complex network.

Source	Sink	Output
4	9	0;
4	15	0;
…		
4	45	0;
4	45	1;
…		

(38); sink nodes: project charter (3); output nodes: repository (0), develop project management plan (4), plan scope management (9), collect requirements (10), define scope (11), plan schedule management (15), plan cost management (22), plan risk management (36), and identify stakeholders (46).

The aforementioned is described by Table 1, which contains 47 rows although only 1 is shown as an example.

Each output node can connect with other nodes and so on until the update/change of information is completed.

For example, when node 4, an output node, is updated/modified, it connects with the sink nodes, which in turn connect with the output nodes, and this process is repeated until all the related information is updated/modified (see Table 2). The table contains 403 rows although only a few are shown as an example.

The graphical representation of this dynamic, both of the nodes (which do not change) and the connections (which change with time), displays the different states as the complex network evolves. Using the previous example, this dynamic is depicted through the complex network represented in Figures 3, 4, 5, and 6, which form a sequence through time.

As depicted in this subsection, a change of states is observed, given by the dynamics of nodes and the dynamics of edges. For this example, activation starts at nodes 1 and 38, which process information; once they receive (red color), they then establish connections with node 3; once they do, nodes 1 and 38 send information (blue color), and node 3 receives information (yellow color), with an active connection (purple color). Then, node 3 processes the received information (red color). This process occurs repeatedly until connections ready for information processing are established.

Another way to understand the dynamics of nodes and connections, related to the previous example, is depicted in Figure 7 as a temporal network [87].

(i) Initial state: nodes 1 and 38 process information concurrently (red color), in an amount of time determined by the discrete uniform distribution.

(ii) Next state: nodes 1 and 38 transmit information (blue color), node 3 receives information (yellow color), and the connection between nodes 1-3 and 38-3 is active (purple color).

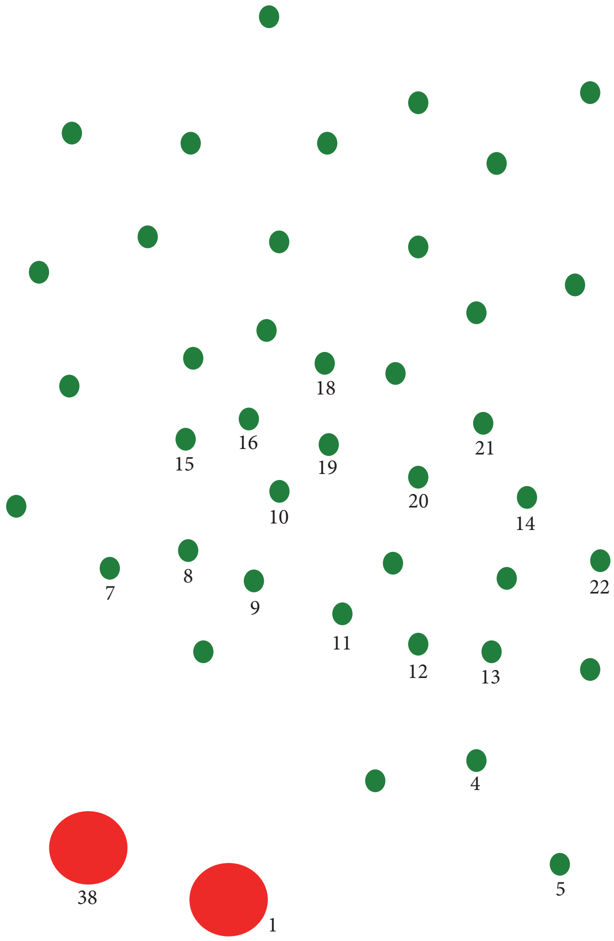

Figure 3: Nodes 1 and 38 process information.

(iii) Next state: node 3 processes information (red color), nodes 1 and 38 are idle (green color), and connections between nodes 1-3 and 38-3 are inactive (black color).

(iv) The process continues.

3.4. Results and Discussion of the Complex Network of Subprocesses Simulation.

The results are described based on the simulations performed with the software created for that end. Not all the graphs can be displayed owing to space constraints.

The results of the simulation are as follows.

(i) Based on the discrete uniform distribution considered previously for calculating times, a duration of 21,068 units of time for the planning phase and of 4,115 time units for the executing phase is obtained (summing to a total of 25,183 time units up to the end of this phase). The monitoring and controlling phase has a duration of 5,028 time units (summing to 30,211 time units); and the closing phase has a duration of 90 time units (giving a total of 30,301 time units). Thus, the total time taken by the simulation is 30,301 time units. As mentioned previously, a discrete uniform distribution taking values between 1 and 11 is

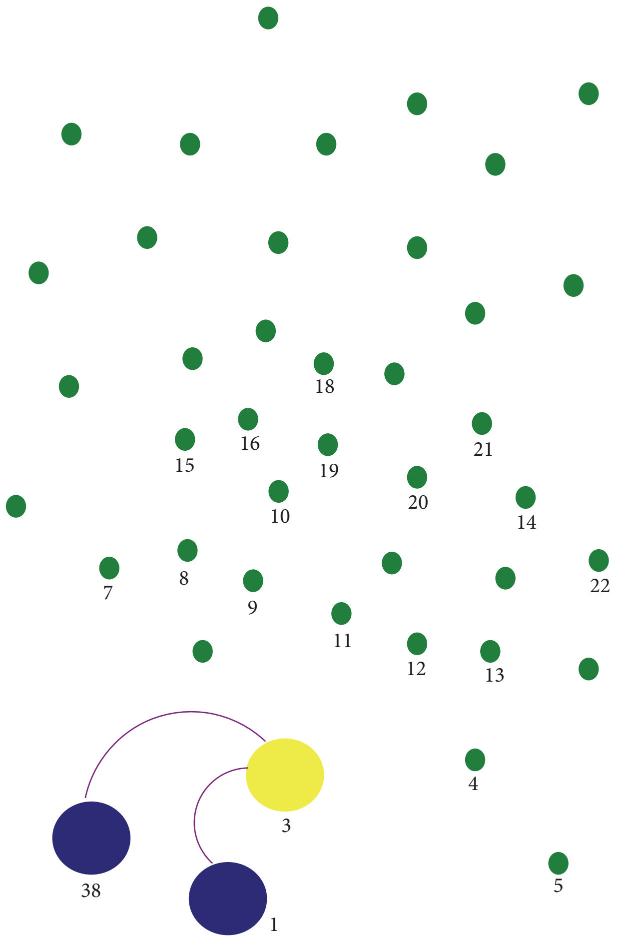

Figure 4: Nodes 1 and 38 send information and node 3 receives it.

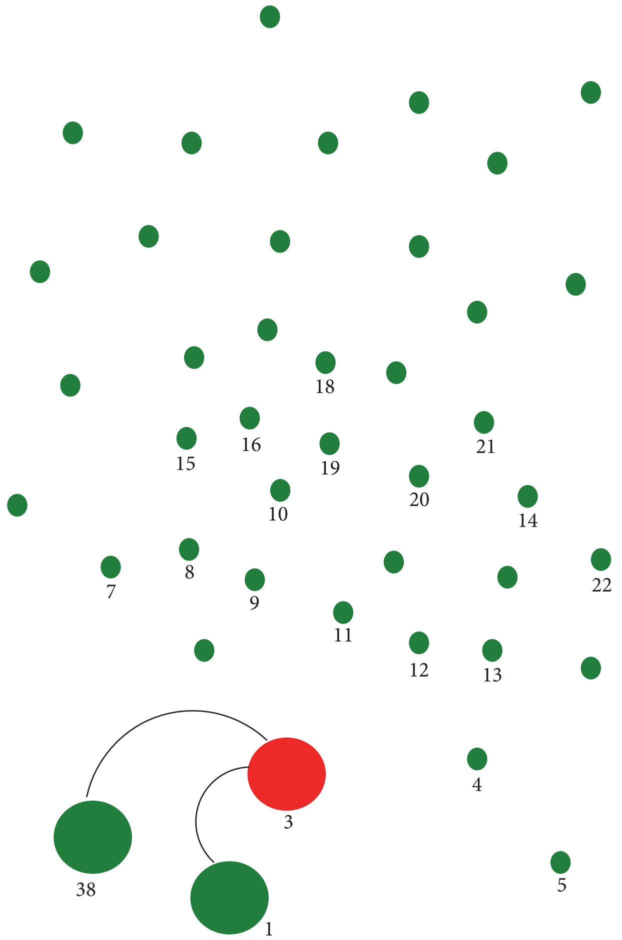

Figure 5: Nodes 1 and 38 are idle and node 3 processes information.

used, to determine both the duration of information processing of each node and the delay time of each connection between two nodes.

(ii) There are 45,145 degrees of the complex network (90,290, input and output degrees) (see Figure 8). This means that the node repository has the greatest number of connections to other nodes given that it is where all the information of the project is stored. The rest of the nodes most relevant to the complex network are the following: develop project management plan, develop schedule, identify risks, and plan procurement management. Therefore, it can be concluded that these nodes are the most likely to be updated or modified. We later define these nodes as strong nodes, because they connect with the greatest number of other nodes.

The nodes with greater degree are the following.

(i) Node repository (0), degrees: 12,194

(ii) Node developing project management plan (4), degrees: 6,194

(iii) Node developing schedule (20), degrees: 5,908

(iv) Node identifying risks (37), degrees: 4,981

(v) Node planning procurement management (42), degrees: 4,539.

The nodes with the smallest degree are the following.

(i) Node planning scope management (9), degrees: 313

(ii) Node planning cost management (22), degrees: 312

(iii) Node planning schedule management (15), degrees: 323

(iv) Node planning risk management (36), degrees: 344

(v) Node planning risk responses (40), degrees: 353

(vi) Node of qualitative analysis of risks (38), degrees: 354

(vii) Node of quality control (28), degrees: 450.

Therefore, the node planning scope management has the least number of connections to other nodes. In addition, these nodes, where only the baselines of the project are determined (schedule, costs, and risks), are less likely to be modified/updated. Thus, they are less important than other nodes are for project management, and thus we define them as weak nodes in project management.

Below, the nodes with the greatest degrees in the complex network simulation are displayed (see Figures 9, 10, and 11).

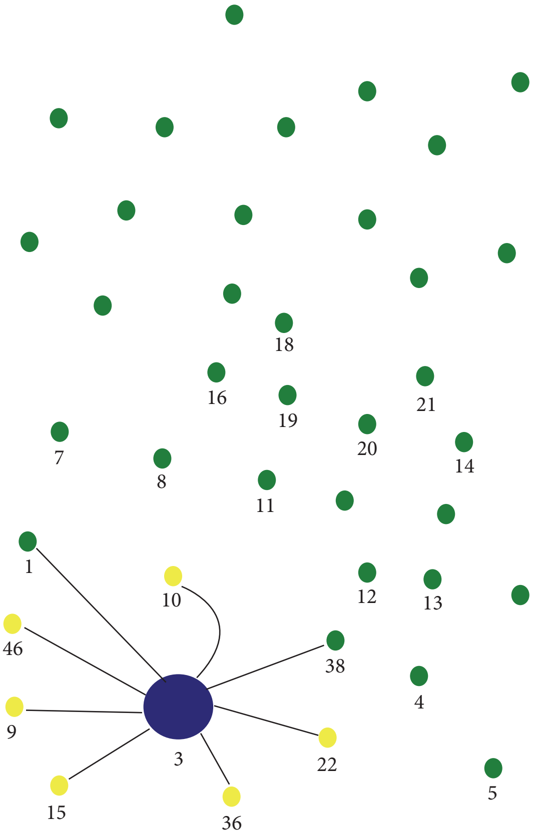

Figure 6: Node 3 sends information to other nodes.

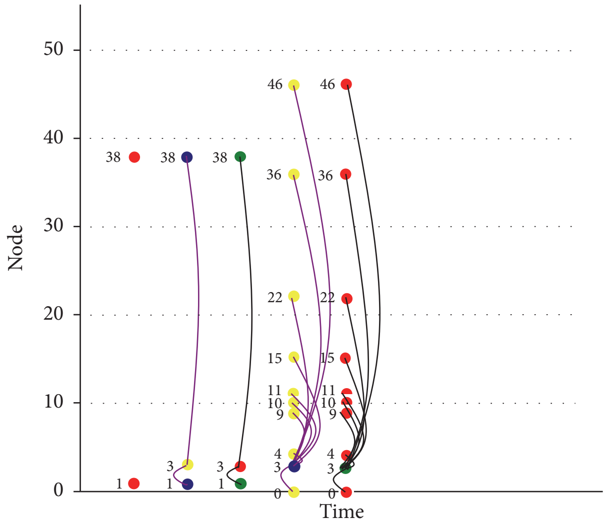

Figure 7: Temporal complex network. The dynamics of nodes and connections are depicted. See the text for the definition of the colors and axes.

The planning phase starts at the beginning, the executing phase starts after 21000 time units, the monitoring and controlling phase starts when 25000 time units have passed, and the closing phase starts when the number of time units is 30000.

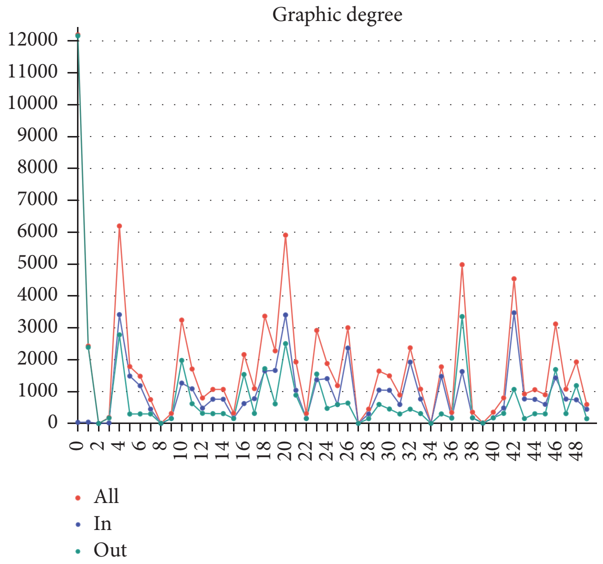

Figure 8: Degrees of the 49 nodes; the result of a full simulation. Degrees, input degree, and output degrees are depicted as a result of the simulation. The degrees are colored red, the input degree is colored blue, and the output degree is colored green.

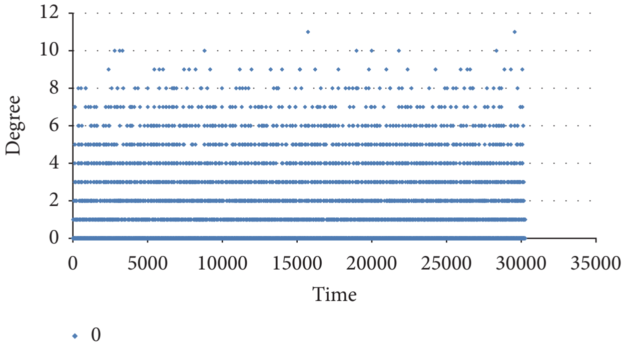

Figure 9: Degree of node 0 (repository), throughout the simulation.

In Figure 9 corresponding to node 0 (repository), there is the same pattern of behavior of the degrees in this node throughout the five phases (planning, executing, monitoring and controlling, and closing). However, some peaks are noticeable during the planning phase.

In Figure 10 corresponding to node 20 (developing schedule), the behavior of the degrees of this node is high during the planning and execution phases. Thus, this node is likely to be modified/updated in these two phases but is not as likely to do so in the monitoring and controlling and closing phases.

Using the results of the simulation of all nodes, produced by the software developed for that goal, it is concluded that node 4 (developing project management plan) is the second highest degree node on average and is the node most vulnerable to changes/updates, given the high rate of modifications to it throughout the simulation. Therefore, it is a strong node in the network. Based on the results of the computation of node degrees, strong nodes and weak nodes

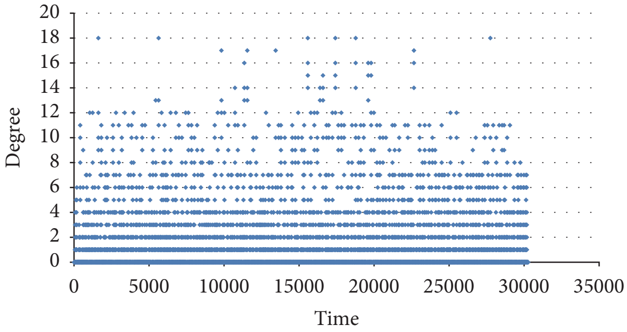

Figure 10: Degree of node 20 (developing schedule), throughout the simulation.

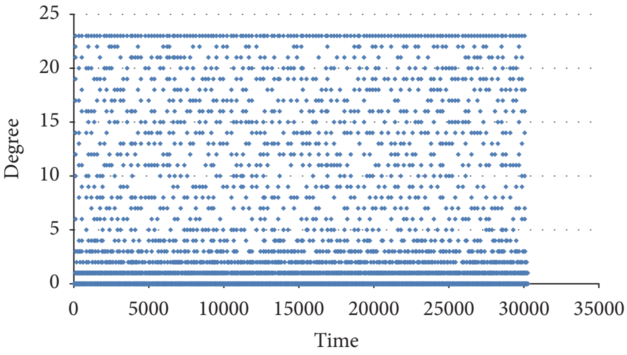

Figure 11: Degree of node 4 (developing project management plan), throughout the simulation.

can be identified in the complex network as a product of the project management simulation.

Strong nodes are defined as those with a higher degree during the simulation could be more vulnerable to modifications and have a higher degree of connections with other nodes. In the previous example, the strong nodes are 0, 4, 20, 7, and 42.

On the other hand, weak nodes are defined as those with a smaller degree during the simulation, those that could be less vulnerable to modifications, and those that have a lower degree of connections with other nodes. In the previous example, the weak nodes are 9, 22, 15, 36, 40, 38, and 28.

It can be inferred that if a strong node is not activated (e.g., from a lack of information), the project could be in a greater state of uncertainty.

The definition of strong and weak nodes, and their potential activation, is essential and new in complex project management given the elucidation of critical nodes. These critical nodes require more attention to succeed in projects of great complexity.

The following are other important measurements of the complex network.

(i) Assortativity: −0,01052: If the value is <0, then the relationships in the network are established between nodes of different degree. In project management, this is because a node can in turn update/modify a secondary network, and nodes with higher degree interact with nodes with lower grade.

(ii) Density: 18.42653: Such a high density is noteworthy, given that it could indicate a high effect of new information in the system because there are nodes connected to other nodes, those ones connected to others, and so on. Thus, updates produced by new or modified information add complexity to project management.

(iii) Diameter: 3: it is the maximum distance between two nodes in the network. In project management, the diameter measurement yields a measure of how far away the nodes can be.

(iv) Adjacency: the nodes with the greatest adjacency are the following.

   (a) Node 42 (plan procurement management) with node 37 (identify risks): adjacency value 1.055
   (b) Node 42 (plan procurement management) with node 0 (repository): adjacency value 903
   (c) Node 42 (plan procurement management) with node 10 (collect requirements): adjacency value 899
   (d) Node 20 (develop schedule) with node 4 (develop project management plan): adjacency value 776
   (e) Node 20 (develop schedule) with node 0 (repository): adjacency value 775
   (f) Node 19 (develop project management plan) with node 0 (repository): adjacency value 602.

Nodes with higher adjacency are those that are in groups of nodes with higher degree. In this case, they are node 42 (plan procurement management) and node 20 (develop schedule). These nodes in the project management are strong nodes that generate connections with a high number of other nodes, being strong nodes in the complex network.

(i) Betweenness: nodes with the highest values are the following: node 0 (repository): 809.949, node 4 (develop project management plan): 486.7958, and node 20 (develop schedule): 123.04543. These are strong nodes through which the most amount of information passes, with the most amount of control over the network.

(ii) Closeness: node 2 (novelties): 0.02; node 8 (close the project or phase): 0.342657343: For the analysis, node 2 can be ignored because throughout the simulation the possibility of novelties was not included. Thus, node 8 is closest to the center of the network. The node closest to the center of the network can be considered that where the simulation ends, because either a phase of the project ends there, or the entire project ends.

(iii) Clustering: node 1 (repository) is the most connected node throughout the simulation, given that it is where all the information is stored.

4. Discussion and Conclusions

The classic perspective is not sufficient to understand the high number of interrelations established in the different phases of a complex project. Thus, project management should be approached from the perspective of complexity, and a complex project should be understood as a complex system. Using the algorithmic methodology established in this study, a modeling scheme can be constructed for any type of project. This is the main contribution of this work, and the stochastic simulation and subsequent analysis are one of the fundamental results of this research.

Weak nodes and strong nodes can be identified, thereby identifying the most vulnerable nodes to be modified/updated and those that, if not activated, could generate higher thresholds of uncertainty for a project. The strong nodes in the standard structure of PMBOK are node 4 (develop project management plan) and node 20 (develop schedule). The weak nodes are node 9 (plan scope management) and node 22 (plan cost management).

The strong nodes in the standard structure of PMBOK are node 4 (develop project management plan) and node 20 (develop schedule). The weak nodes are node 9 (plan scope management) and node 22 (plan cost management).

These results suggest that, given PMBOK, the scope and costs should have almost no changes/updates throughout the management of the project. In addition, the classic perspective assumes that behavior is deterministic from planning to closing of the project or phase. Thus, some rigidity can be established in the nature of the project when it is in a complex situation.

Given this, the following important question arises. What happens if nodes 4 and 20 disappear from the network (e.g., if they fail to be activated because of a lack of information)? To answer this question, new simulations are run in which nodes 4 (develop project management plan) and 20 (develop schedule) are not activated in the modeling of the network.

The results are as follows.

(i) Degrees: 29,552, with a 32% decrease from the initial simulation (degrees: 90,290): This confirms that the mentioned nodes have a significant influence over the others and that the information outputted from such is important for the project management. Higher levels of uncertainty are generated by the absence of the nodes, which is key for the project.

(ii) Density: it is 6.031020, with a 32% decrease from the initial simulation (density: 18.42653).

(iii) Diameter becomes 4, increasing the maximum distance between two nodes in the network. This suggests that the nodes (4 and 20) are bridges that aid in the flow of information throughout the network.

Another conclusion is that increasing importance should be attributed to the use of tools based on the science of complexity in order to interpret complex project management, given that they provide additional information not available from classic-perspective tools.

Finally, the structure of the process network described can be used in the future to advance different types of simulations for any type of project. In particular, any sequence in the construction of the network can be simulated. As new information is delivered, the network updates the nodes/subprocesses as required.

This study establishes measurements of uncertainty, efficiency, and robustness, based on the complex network, which can be interpreted for the management of complex projects. This enables decision making prior to the start of the execution of a project. The report of this research will be described in a future article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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