A Dynamic Model of the Effects of Project Complexity on Time to Complete Construction Projects

Reda M. Lebcir and Jyoti Choudrie

***Abstract*—The aim of this paper if to investigate the factors driving project complexity in construction projects and how they impact on project cycle time. This issue has been addressed by building a framework for project complexity for construction projects and evaluating is impact on project cycle time through a System Dynamics (SD) simulation model integrating project complexity, project operations, and its time performance.**

The results indicate that project complexity is driven by four factors: Project Uncertainty, Infrastructure Newness, Infrastructure Interconnectivity, and Infrastructure Size and that Project Uncertainty is the most influential factor on project cycle time comparatively to the other factors.

***Index Terms*—Project management, Project complexity, Project cycle time, System dynamics**

I. Introduction

Successful management of innovation in the construction industry is becoming increasingly crucial to the performance of companies in this sector. However, this is a daunting task as rapid changes in clients' requirements coupled with a high rate of technological innovation have increased the difficulty to deliver projects in line with planned time objectives [1]-[5].

One of the influencing reasons explaining the project poor time performance is the level of "project complexity" in the project [2],[6]. However, the factors driving "project complexity" are not yet well defined. There is an urgent need for developing a framework for project complexity in construction projects. This is important as project management activities such as planning, co-ordination, control, goals determination, organizational form, and project resources evaluation and management are all affected by the level of complexity in a project [7],[8]. The effectiveness of these processes and techniques is a strong determinant of the construction project cycle time, hence the link between project complexity and construction project cycle time.

There are, consequently, two issues warranting investigation in this context. First, what are the factors driving "project complexity" in construction projects. Second, what is the impact of these factors on construction projects cycle time. It is important to remember that different project complexity factors are present simultaneously in the construction project, however their level and relative influence on the construction project cycle time are independent and different. For example, the decision regarding the level of technological uncertainty in the project is independent from the size of the project and the number of elements involved in it [1]. Whilst it is implicitly known that all these factors contribute to make the project difficult and complicated to manage, hence impacting the construction project cycle time performance, it is not fully known how each factor taken individually affects the construction project time performance. The aim of this paper is, therefore, two folds: First, to develop a "project complexity" framework for construction projects. Second, to evaluate the relative influence of each of these factors on the construction project cycle time. The paper is organized as follows. The first section focuses on the construction project complexity framework. This is followed by a description of the conceptual framework and the construction project simulation model developed in this research. A description of the simulation scenarios tested on the model and the analysis of their results are then presented. The paper concludes with a discussion and a conclusion including the main findings of the research.

II. Project Complexity Factors

Although there is an implicit acknowledgement among practitioners and academics that construction projects are becoming more and more complex over time, there is still a great deal of confusion about the factors driving this complexity [6], [9], [10]. Thus far, there has not been a single comprehensive framework which includes and integrates all the aspects of project complexity in the context of construction projects. Concepts such as, "structural complexity", "project scope", "technological novelty", "technical risk", "technical uncertainty", "project size", have been used interchangeably to represent similar factors and without clear reference to how these factors relate or affect "project complexity" in construction projects

For this reason, a new project complexity framework, which is grounded on previous project management literature related to project complexity in different contexts including innovation and new product development projects [6], [7], [9], [11], has been developed in the current research. The framework indicates that project complexity in construction project is driven by the following factors

Infrastructure Size (IS): This refers to the size of the infrastructure to be delivered at the end of the project. It is determined by the number of elements (components, parts, functions, tasks, specialists ...) included in the infrastructure. This makes the project more complex as there is an increased volume of work and the need to coordinate the different

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elements in the project.

Infrastructure Interconnectivity (II): This represents the degree of "integration" and "linkages" between the different elements of the infrastructure. Interconnectivity is important from a project management perspective because of its significant impact on the rework and coordination activities in the project. If infrastructure interconnectivity is high, it means a change in one element of the project may lead to changes in other elements of the project causing rework on tasks which have been already completed. This, in turn, requires significant levels of coordination and information exchange between the teams working on different elements of the project.

Infrastructure Newness (IN): This represents the portion of the infrastructure to be innovated from previous projects delivering the same type of infrastructures. A high level of infrastructure newness indicates that most of the elements of the infrastructure are new to the project. This has implications for the management of the project as the volume of work increases and requirement for integration between the new and old elements in the infrastructure become more important. As a consequence, coordination activities in the project become significant as it is important that teams working on different parts of the project execute their tasks in a timely and coherent way.

Project Uncertainty (PU): This reflects the level and extent of the gap between the knowledge required to perform the project tasks and the knowledge available to the project team at the beginning of the project.

Project uncertainty renders the project complex to manage because the suitable means, methods, and capabilities to be deployed in a project are not always well known at the start of project work. Project uncertainty requires significant efforts from the project team to create and disseminate this knowledge so that the project work can be executed. High degrees of project uncertainty have been found to be associated with significant levels of error generation and rework, requires project members to go through many iterations before solutions to proceed with the project work are found

III. Simulation Model Description

The System Dynamics (SD) simulation model [12] presented here is grounded on and combines the findings of (i) the construction project management literature and (ii) previous SD models in which many feedback structures central to project dynamics have been identified, simulated, and validated. Such processes include work progress, schedule pressure and alteration, productivity, workforce level, error discovery and correction, quality assurance activity, project scope, perceived versus real progress, developers learning and experience, normal and overtime work, project priority, coordination mechanisms [13]-[15].

The simulation model includes several phases reflecting the evolution of construction projects over time. Each phase is simulated through a model incorporating several interlinked sectors such as planning, execution process, human resource management, work allocation, and productivity.

A. The Work Process Sub System

The work process sub-system simulates the mechanisms determining the execution of the construction project work. Project work execution is represented through the transformations affecting the state of the project tasks in the construction project phase from the initial state of "Tasks for planning" until the final state of "Tasks released" through the intermediate states "Tasks to Complete"; "Tasks Completed Not Checked", "Tasks in Rework", and "Tasks Approved".. These transformations are determined by the project activities, which include planning (gathering information about a task execution), base-work (executing a task for the first time), quality assurance (checking tasks for flaws) rework (correcting flawed tasks), and internal co-ordination (communicating with other staff in the project phase).

The planning activity generates the necessary information, which enables project members to carry out the execution activities in the project. During the planning phase, the project team performs technological evaluation of the current capabilities in the organization with the project requirements, specify the resources needed to complete the project, identify sources of risks and challenges and how to deal with them, determine key project participants, create the project breakdown structures and the associated schedule and resources plans, and define sources of required functional support needed to carry out the project work.

Once tasks are planned, they are not released immediately for execution. The information generated by the planning process is kept for a while until a sufficient amount of information is available to allow the start of the project work execution.

The project execution process starts by the execution of the project tasks. The rate at which tasks are executed, that is the number of tasks executed per unit time, is determined by the base-work activity (the execution of a project task for the first time). Completed project tasks are checked for possible flaws. If a task passes this checkpoint successfully, it is approved. Otherwise, the task will have to be corrected (reworked). Once flawed tasks have been reworked, they are checked again for possible flaws. It is important to notice here that because project staff are not perfect in detecting flaws, some of the tasks which are flawed go undetected and are, consequently, approved and then released. The flawed tasks due to the execution of project work are not the only tasks to be reworked. Sometimes, if some tasks are found flawed, the tasks which are connected to them and already approved may have to be reworked again. Once these tasks have been approved for rework, they have to be coordinated by the project team responsible for generating flawed tasks due to execution and the project team who executed the tasks which become flawed due to infrastructure interconnectivity. These teams meet to decide about the best course of action to rework the extra flawed tasks.

B. The Human Resource Management Sub-System

The execution of any project cannot be accomplished unless the right mix of resources is deployed in the project. In the particular case of construction projects, it has been observed that resources play a central role in allowing a successful completion of projects. If a project is suitably

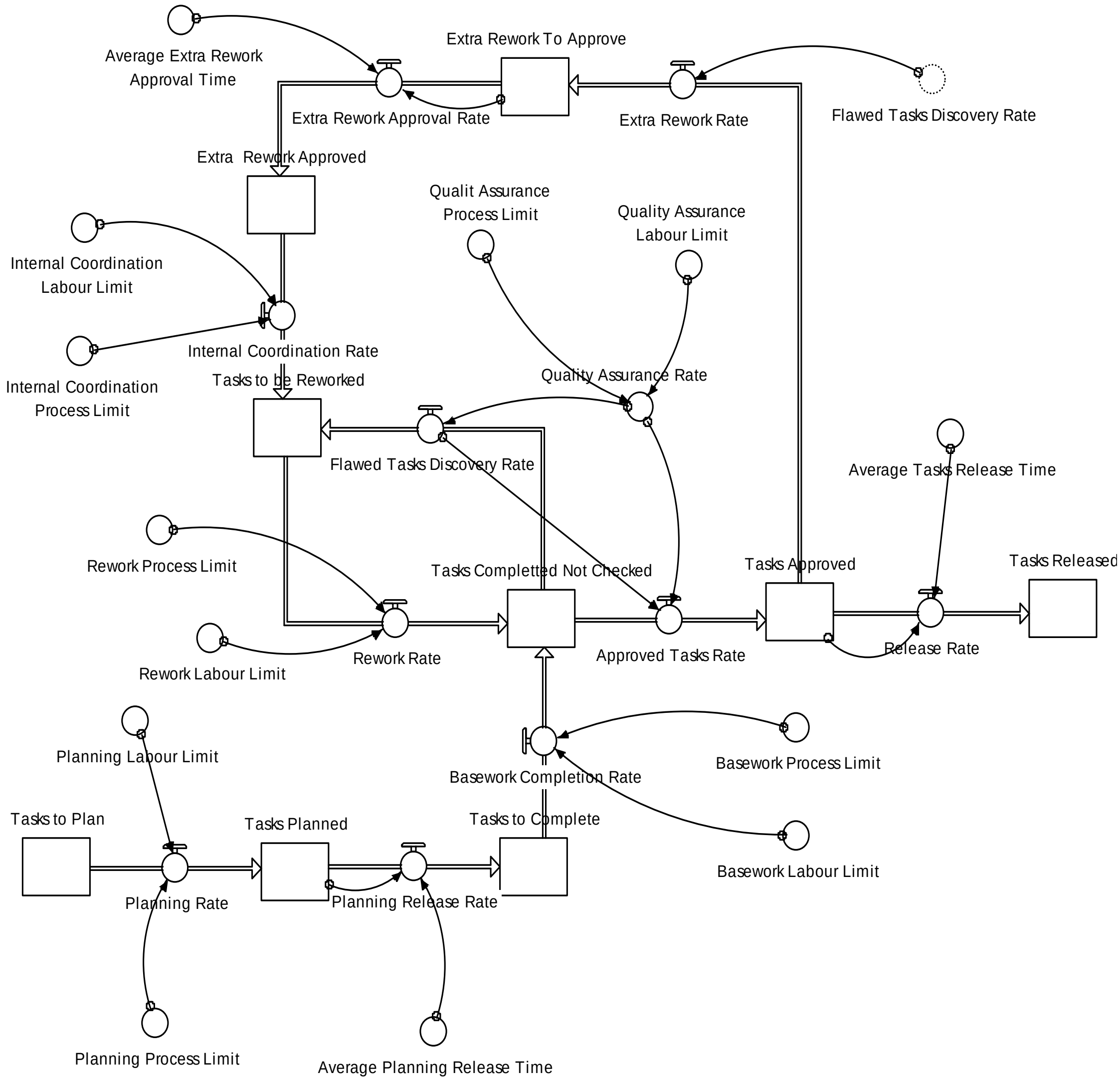

Fig. 1. Evolution of tasks states in the execution process subsystem.

staffed with the right level of project workers possessing the required skills and experience, and supplied with the right equipment and material, the project work will be carried out without delays and with a high execution quality. In the current model the focus is on the availability and quality of project workers. This is portrayed in the human resources management, which represents the policies driving the requirements to execute the project activities. It is assumed that the total size of the workforce (in terms of the number of workers needed in the project depends on the total labor required to execute all the project activities as determined by the state of the project work progress at any given time in the project. The fraction of the total labor directed to execute each project activity is proportional to the number of project tasks available to undergo the project activity at any given time in the project.

The effect of the project complexity factors on the project operational variables is represented through a set of non-linear functions, where each non linear function links an input variable representing the project complexity factor to an output variable representing the effect of the project complexity factor on the project operational variable it affects. As such it is easy to represent the effects of the four project complexity factors on all the operational variables in the project.

C. Model Parameterization and Validation

The model parameters were determined in a number of ways. Some parameters were readily available on the project documents (for example the number of workers in the project). Other parameters were estimated from the project progress reports and from observations of the project work (for example the average time for the project activities). The last category of parameters was estimated based on the judgment and experience of the project team (for example, effects of fatigue on project work productivity). Validations tests were performed on the model [12]. The qualitative structure of the model was validated through workshops involving several project teams in the organization. The quantitative structure of the simulation model was validated by a thorough check of the model equations and variables and by performing extreme conditions tests on the model. The behavioral reproduction tests were performed through comparison of the simulation model outputs and the real world behavior of a large set of variables on different phases of the project.

IV. Scenarios and Results Analysis

The experiments on the model were conducted by varying the level of the four “project complexity” factors. Each of the four project complexity factors, that is “Project Uncertainty” (PU), “Infrastructure Newness” (IN), “Infrastructure Interconnectivity (II), and “Infrastructure Size” (IS), was assigned three different levels defined as “*Low*”, “*Reference*” and “*High*” [16], [17]. A scenario represents a project in which each of the four project complexity factors is assigned one of the three levels mentioned above. For example, a project in which PU is low, IN is reference, II is reference and IS is high is a scenario. Given that we have four project complexity factors each accepting 3 possible levels, the number of possible scenarios is equal to the number of combinations of 4 factors and 3 levels, that is (3^4) or 81.

The impact of the four project complexity factors on the construction project cycle time is analyzed separately for each project complexity factor. The rationale being that the levels of the project complexity factors are determined in projects independently from each other and impact construction project cycle time separately [1]. Therefore, for each project complexity factor, graphs are constructed to represent the change in the cycle time as the level of the factor changes from “Low” to “Reference” to “High” for the same combination of the levels of the remaining three project complexity factors. For example the graph representing the impact of PU on cycle time (Fig. 2) represents the cycle time for the three levels (Low, Reference, High) for the same combination of the remaining three factors IN, II, and IS (in this order). This enables the analysis of the impact of the PU factor without interference from the other project complexity factors.

In addition, and in order to understand better the influence of the project complexity factors on the construction project cycle time, the average cycle time, for every level of each factor, is presented in Table I. For example, the average cycle time for all projects with low PU is 638 days and for all projects with high II is 1285 days.

TABLE I: AVERAGE PROJECT CYCLE TIME FOR ALL LEVELS OF THE PROJECT COMPLEXITY FACTORS (IN DAYS)

	Low	Reference	High
PU	638	1150	1378
IN	939	1084	1144
II	766	1115	1285
IS	884	1120	1215

The impact of each project complexity factors is discussed in the following section

- **Project Uncertainty (PU)**

The effect of project uncertainty on development cycle time is presented on Fig. 2. It is clear that project cycle time is affected by project uncertainty as it tends to increase as the level of PU changes from low to reference to high and this is valid regardless of the levels of the other project complexity factors IN, II, and IS. However, the increase in project cycle time is not of the same magnitude as PU level increases. Project cycle time goes up much more sharply when PU increases from low to reference than when it moves from reference to high. As an illustration the average project cycle time leap is four times more important when PU moves from low to reference (from 638 days to 1150 days) than when PU moves from reference to high (from 1150 to 1378 days).

- **Infrastructure Newness (IN):**

The impact of IN on project cycle time is less dramatic than that of PU. In fact although, as Fig. 3 indicates, changes in project cycle time show an ascending trend as IN becomes higher, this change is not substantial. This is especially the case as IN changes from reference to high. This observation is strengthened by the fact the average project cycle time increases with 15% (from 939 to 1084 days) as PN changes from low to reference and only by 5% (from 1084 to 1144 days) as PN changes from reference to high.

- **Infrastructure Interconnectivity (II)**

Fig. 4 shows that II is a factor which influences project development cycle time, which climbs as the level of II moves up. This observation is valid for all combinations of the remaining project complexity factors PU, IN, and IS. In other words, regardless of the decisions determining the level of PU, IN, and IS, a project with higher levels of II will require more time to complete. The other important finding from Fig. 4 is that the influence of II tends to be more significant as II changes from low to reference than if it changes from reference to high. As an illustration, the average project cycle time varies by 45% (from 766 to 1115 days) as II changes from low to reference, but varies only by 15% (from 1115 to 1285 days) as II changes from reference to high.

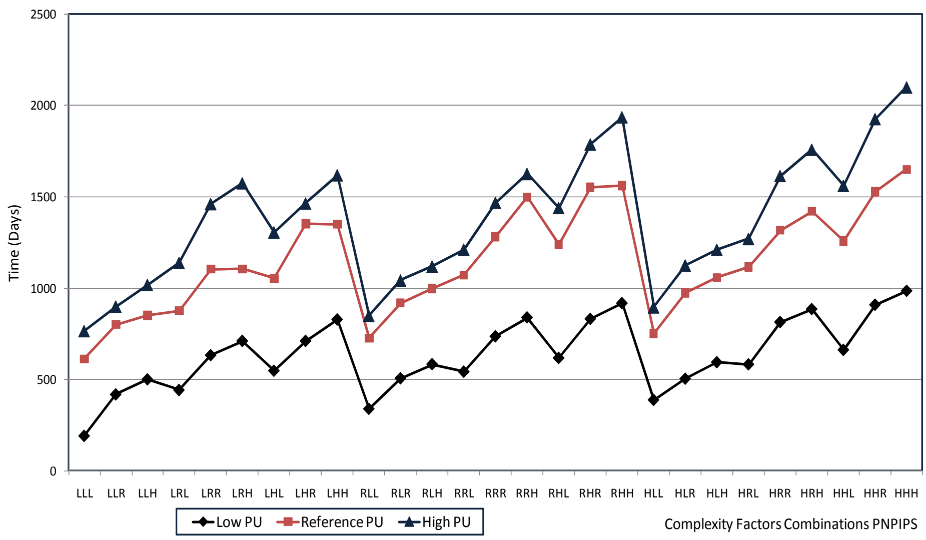

Fig. 2. Project cycle time for the 3 levels of Project Uncertainty (PU).

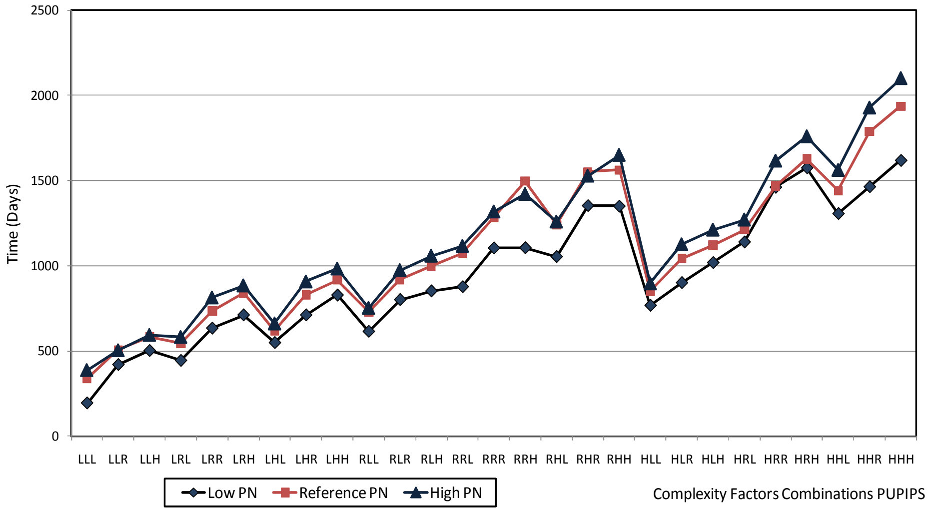

Fig. 3. Project cycle time for the 3 levels of Infrastructure Newness (IN).

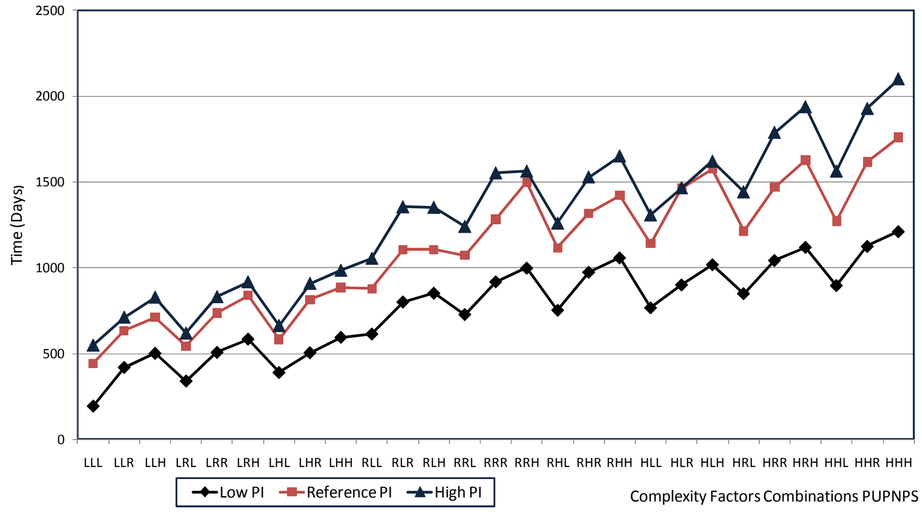

Fig. 4. Project cycle time for the 3 levels of Infrastructure Interconnectivity (II).

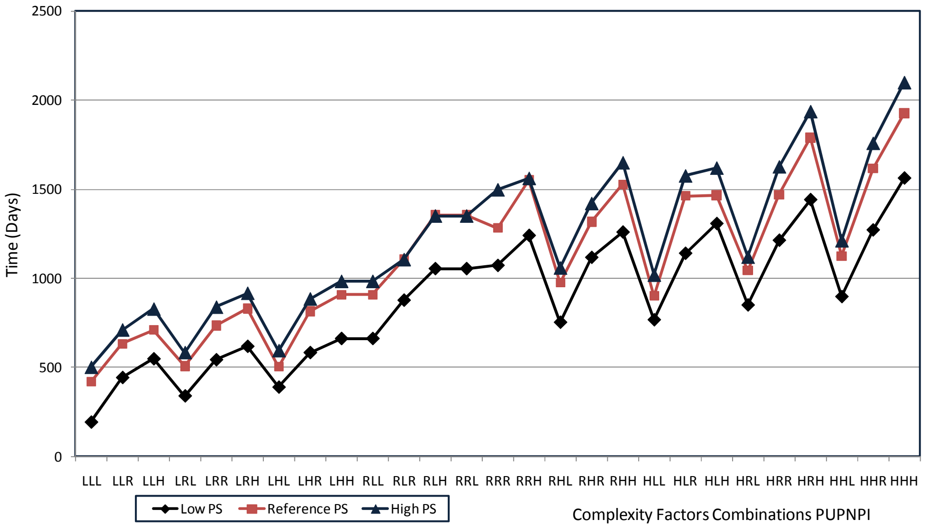

Fig. 5. Project cycle time for the 3 levels of Infrastructure Size (IS).

- **Infrastructure Size (IS)**

IS appears, from Fig 5, to be the project complexity factor associated with the lowest influence on project cycle time. Of course, project cycle time grows as IS increases, however to a less extent than the other project complexity factors. In this context, the average project cycle time is 884, 1120, and 1215 days for low, reference, and high IS respectively. In percentage terms, the increase is around 26% from low to reference and 8% from reference to high. Further evidence to this observation can be seen on Fig. 5. The change in project cycle time is more important from low to reference IS than from reference to high IS.

V. Discussion and Conclusion

The aim of this paper is to understand the influence of project complexity on construction project cycle time. This issue was investigated in two steps: (i) development of a project complexity framework for construction projects and (ii) building of a System Dynamics (SD) computer simulation model representing a multi-phase project.

The construction project complexity framework is grounded on the project complexity framework developed in the project management literature [7], [11]. The analysis of this literature led to the development of the project complexity framework in this research and which includes four factors driving project complexity in construction projects: (i) Project Uncertainty. (ii) Infrastructure Newness, (iii) Infrastructure Interconnectivity, and (iv) Infrastructure Size.

The SD simulation model built in this research constitutes a step further in the successful application of SD in Project Management. The model combines the project management and SD literatures and sub-models and integrates the project complexity framework developed in this research and the construction project operational variables such as project tasks, project management decision making processes, resource management, project objectives, top management support, and so on. As such the model combines both the strategic and operational decisions and policies of the construction project.

The simulation results yielded some interesting findings. It is crystal clear than project complexity factors have an inflating effect on project cycle time and this is valid for each of the four project complexity factors. The implication of this is that project managers must be aware of this finding as they make the strategic decisions (which determine the level of the project complexity factors) during the planning and formative phases of the project. Decisions regarding the level of technological innovation to be used in the project, the breadth and depth of the technologies to include in the project, the fraction of the new elements to be included in the infrastructure, the size of the infrastructure, the level of the linkages between the elements of the infrastructure, will have significant influence on the project cycle time. Project managers must resist the attempt of overlooking or ignoring the consequences of their strategic decisions as these have a significant impact on the level of project complexity, the operational evolution of the project, and ultimately its time performance.

In addition, the research yielded some interesting finding regarding the effect of each of the project complexity factor on project cycle time. Project uncertainty, which reflects the depth of the innovation in the project, is clearly a strong determinant of the time required to complete the project. Projects involving medium or high innovation are associated with far longer completion times than project involving low innovation. When making decisions determining the level of innovation in the project, project managers must make a trade-off between its effects on the project cycle time, and the other objectives of the project linked to the competitive environment, the project financial rewards, and so on.

Interestingly enough, there seems not to be a great difference between project involving medium and high levels of innovation in term of project cycle time. The managerial consequence of this is that if there is a choice between the two options of medium and high innovation, it is better to choose the former option especially if this does not affect significantly the expected success of the product in the market.

The impact of Infrastructure Newness on project cycle time is less acute than that of project uncertainty. This finding has important consequences for the management of construction projects. Unless the target is to build a low innovation infrastructure, there is no significant difference in terms of the impact of IN on cycle time when its level is medium or high. Other considerations (financial, strategic,...) should be taken in account when faced with these two decisions (medium or high IN).

The structure of the infrastructure (Infrastructure Interconnectivity) is influential on project cycle time. Projects in which the structure is tightly linked take longer to complete than projects in which the linkages are less integrated. Therefore, whenever possible project managers are advised to choose a low II structure as this reduces cycle time. If, this is not possible, then the impact of II is not very different if an infrastructure with medium or high interconnectivity is built. In this case, the decision should be driven by other performance criteria than project cycle time. As intuition suggests, products including a higher number of elements are finished later than projects including a low number. So, it is preferable to reduce the number of elements in a project. However, the results indicate that once this number is above a certain level (medium or high IS), its effect is significantly reduced. In this case, other performance criteria should guide the decision making process to set the level of IS in the project

Although this research has addressed some important research questions regarding the factors affecting project complexity in construction projects and how they relate to the project cycle time, it can be extended in different directions. For instance, it is possible to include other performance indicators (cost, quality, finance,) in the model. In addition, it would be interesting to see how these factors interact with some operational decisions such as the use of Cross Functional Teams in the project. Another possible extension to the research will be to explore the trade-off between the structural complexity element (Infrastructure Size and Infrastructure Interconnectivity) with the innovation element (Project Uncertainty and Infrastructure Newness) of project complexity and its impact on project performance.

In conclusion, it can be said that this research has shed some light on the impact of the construction project strategic decisions on project cycle time using an innovative tool (computer simulation modeling). Further research is, however, required to further improve our understanding about the relationship between the strategic, operational, and the performance aspects of these projects.

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