Conceptual methodology for managing transportation construction projects through the use of buffering strategies

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ABSTRACT

Uncertainty is an inherent part of production systems. In construction processes, production variability emerges as one of the most typical representation of uncertainty. Negative variability impacts in construction demands effective solutions to mitigate its effects on the accomplishment of projects. The incorporation of buffers constitutes powerful tools to resolve uncertainty problems in construction processes and to optimize the construction operations sequencing. Despite the fact that buffering strategies have been implemented in several types of construction projects, there is limited evidence of specific applications of these strategies to highway projects. Based on discrete event simulation modeling, a conceptual methodology of buffering strategies applied to transportation projects is presented.

After an exhaustive literature review, the most relevant buffers in transportation construction projects are presented, followed by conceptually modeling a typical construction process within highway projects. Through this methodology, the authors present an iterative process which allows decision-makers to properly select buffers to be considered when modeling construction processes in transportation construction projects.

Keywords

Construction management, linear scheduling, simulations-based techniques.

1. INTRODUCTION

The early history of construction has been mainly related to magnificent buildings (i.e. Egypt, Greece, etc.), dams, war facilities, and of course, roads. Regarding with roads, the first notions of constructed roads are found around 4,000 BC in the Middle East and in England (Lay and Vance, 1992). Later, during the nineteenth and twentieth century's, the advent of new technologies, such as manufactured asphalt (Lay and Vance, 1992) and prestressed concrete (Marrey and Grote, 2003), allowed the expansion of highway networks. This expansion has reached its highest development level in the US, having the largest highway system in the world, with more than 160,000 miles of highways (Slater, 1996).

After facing a recession in the US (National Bureau of Economic Research, 2007), President Barack Obama signed the American Recovery and Reinvestment Act (ARRA) on February 17, 2009, in order to change the face of the US in terms of improvements to its infrastructure. The ARRA was intended to provide significant new funding for transportation infrastructure, triggering the construction of more than 12,000 road, highway and bridge projects across the US, of which more than 3,000 projects have been completed and more than 8,000 are currently under construction (FHWA, 2010). This new dynamic scenario demands innovative tools to effectively manage transportation construction projects. One of those tools is simulation and specifically buffering strategies.

In terms of simulation and buffering strategies, numerical solutions to engineering problems are usually obtained after running simulation processes, particularly when analytic solutions are not feasible. Simulation techniques are characterized by the repetition of a solving process hundreds or even thousands times, in order to converge to a solution, which consists of mean and standard deviation.

Simulation is applicable to a variety of engineering practices; one of them is linear scheduling techniques, which is particularly useful in projects where the activities are of a repetitive nature (Newitt, 2007). Moreover, buffering strategies have been successfully applied to simulating building construction processes because of their repetitive condition (González et al., 2006). However, not too much attention has been pay to applying buffering strategies to transportation construction projects.

On the other hand, within transportation construction projects, some effort has been put to determine the main reasons which negatively affect the project progress and to establish what activities are more exposed to delays within this type of projects (Thomas and Ellis, 2001).

However, despite the contribution of establishing buffering strategies and determining the main activities to be included into a transportation construction project, both initiatives have not been brought together. This paper presents the buffering strategies commonly used in construction projects and determines the activities to develop a conceptual methodology to apply those buffering strategies into transportation construction projects.

2. LITERATURE REVIEW

2.1. Computer simulation in civil engineering

One of the first experiences based on the use of computer simulations in civil engineering was conducted in the late 70s, when a group of researchers presented an overview of the incorporation of computer simulation for teaching purposes. This study was done over a ten year period in the Department of Civil Engineering at the University of Nottingham (Cullingford et al., 1979) and as a result; students were seen to have benefited from these computer applications in important areas within civil engineering, such as: planning and control of construction projects and negotiation within the construction process. Some years later, also with educational purposes, multimedia tools were successfully applied to civil engineering teaching, giving students the opportunity of interacting with several disciplines of civil engineering, i.e., hydraulics, structures, geotechnical, environmental, marine, and project management, facilitating the learning about the phases of a civil engineering project (Angelides et al., 2000). Other authors have continued to expand the use of simulation as a powerful tool to be included within the teaching of civil engineering (Ang and Tang, 2008).

Simulation has also been successfully applied to diverse areas within civil engineering industry, such as hydraulics and water resources (Nijssen et al., 1997), structural engineering (Takahashi and Fenves, 2006), geotechnical engineering (Oettl et al., 2004) and others (Martinez et al., 1999; Han & Halpin, 2005; Peña-Mora et al., 2008).

Most of those applications have mainly been intended to deal with the complexity of problems where an analytical solution is not feasible. Despite the fact that several simulation approaches have included the use of buffers, just a few researchers have been mainly focused on developing buffering strategies applied to transportation construction projects.

2.2. Simulation within the construction industry

In construction management, as a whole concept which includes not also transportation projects but also all type of construction works, several initiatives have been undertaken in order to improve the way through projects are managed. Within these initiatives, several techniques and tools have been developed; one of them is simulation. More than thirty years ago, Halpin (1973), worked on some of the first methodologies for construction simulation and, nowadays, construction simulation has effectively been applied to building projects (González et al., 2009), earthmoving projects (Peña-Mora et al., 2008), tunnels (Al-Battaineh et al., 2006), among others. Some of these simulations have sought to deal with the negative impacts of variability in construction and its effect in the productivity of projects. Likewise, some models have been developed in order to improve the overall project performance, through reducing variability (Thomas, 2002).

Other important aspects within construction simulation are productivity and buffering strategies. Some researchers have studied the productivity level in this type of projects, emphasizing the importance of understanding how productivity changes over the duration of the project (Ellis and Lee, 2006). In addition, buffering strategies have been developed to deal with errors and changes in concurrent design and construction of civil infrastructure projects, helping protect a planned schedule by absorbing negative impacts of those errors and changes (Lee et al., 2006).

2.3. Buffering strategies within construction industry

There are diverse types of buffers which can be applied to construction simulation: 1) Inventory buffers, mainly characterized by raw materials, Work-In-Process (WIP) and finished goods; 2) Capacity buffers, characterized by redundant labor; and 3) Time buffers, with the main objective of managing production schedules and deliveries on due dates (Hauge and Paige, 2002).

The application of each buffer depends on the type of project and production circumstances, among other variables. Therefore, after determining relevant activities in transportation construction projects (which will be used within the simulation model), this research seeks to find out the appropriate buffers which can be applied to transportation projects. Once these buffers have been determined, the next phase of this research is to propose a simplified linear scheduling model for a transportation construction process and then to simulate this process. Finally, the third phase of this research is to propose a conceptual methodology for managing transportation construction projects.

3. The Proposed Model

The following are the main steps to build the conceptual methodology presented in this paper: 1) Development of a Linear Schedule for the project; 2) Selection of activities to be included in the simulation model; 3) Method for the unification of multiple contract pay items; 4) Selection of proper buffers to be used in the simulation model; 5) Development of a conceptual simulation model; 6) Proposed simulation model and its validation.

3.1. Development of a Linear Schedule for the project

The basic idea involved in this paper is to formulate a general model to simulate a transportation construction project. In order to better represent the progress of the activities, a graphical scheduling technique has been selected. There are several graphical scheduling techniques, such as Line-of-Balance, Time-Space Scheduling and Linear Scheduling method. The latter is characterized by a two-dimensional chart, displaying in the Y-axis the number of units that will be completed within any period of the activity's duration displaying in the X-axis (Callahan et al., 1992). Graphical scheduling techniques are not new. Gorman (1972) was one of the first authors to propose the use of a Time versus Distance diagram, in order to improve the way of communicating schedule information through visual impact in highways, pipelines and other projects characterized by a repetitive nature (high-rise buildings, tunnels, etc.).

Highway projects are well suited for a linear scheduling approach because of their linear nature (one operation or crew follows another sequentially). Transportation construction projects involve activities such as maintenance of traffic, road preparation, paving, etc. Each of these activities can be repeated by the same crew from one end of the project to the other, where the only distinguishing feature among them is their production rates (Callahan et al., 1992).

Newitt (2007) identifies that linear scheduling has its roots in the manufacturing industry. This scheduling technique is particularly well suited for projects where the activities are of a repetitive nature. The types of construction projects that lend themselves to linear scheduling are physically horizontal (highways, pipelines, railroads, etc.) rather than vertical projects; although some components and processes of high-rise buildings and even residential construction could be scheduled with linear scheduling methods due to the repetitive nature of some of those project components. The main objective of linear scheduling is to help project managers better visualize time and space conflicts between activities.

Hinze (2007) and Newitt (2009) suggest the following steps to create a linear schedule: (1) To identify activities; (2) To estimate activity production rates; (3) To develop activity sequences; (4) To create the velocity diagrams and; (5) To look for conflicts and buffers.

The first three steps are usually found in all scheduling methods. However, the last two steps are unique and especially used in linear scheduling.

The key step in linear scheduling is the velocity diagram (Newitt, 2009), also called production rate diagram (Hinze, 2007), which shows the time-space relationship of each activity (Fig. 1).

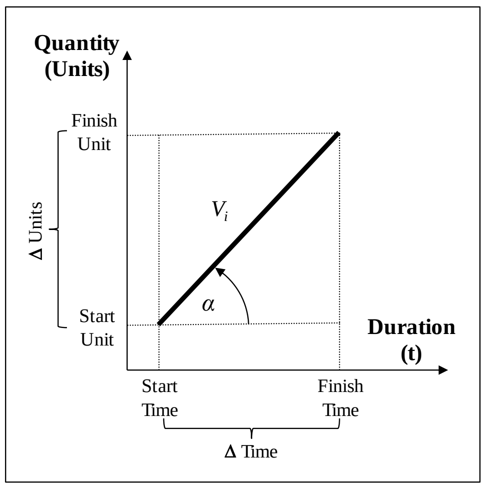

Fig. 1. Production Rate diagram (adapted from Hinze, 2007).

In Figure 1, V_i is the Production Rate and α is the slope of the line. Both are represented by the mathematical expression 1.

$$V_i = \tan(\alpha) = \frac{\Delta \text{Units}}{\Delta \text{Time}} \qquad (1)$$

However, when variability or quantity of nonuniformity which can induce negative impacts on the productivity of a process (Hopp and Spearman, 2000) is taken into account, these production rates are not constant but change period by period (Fig. 2).

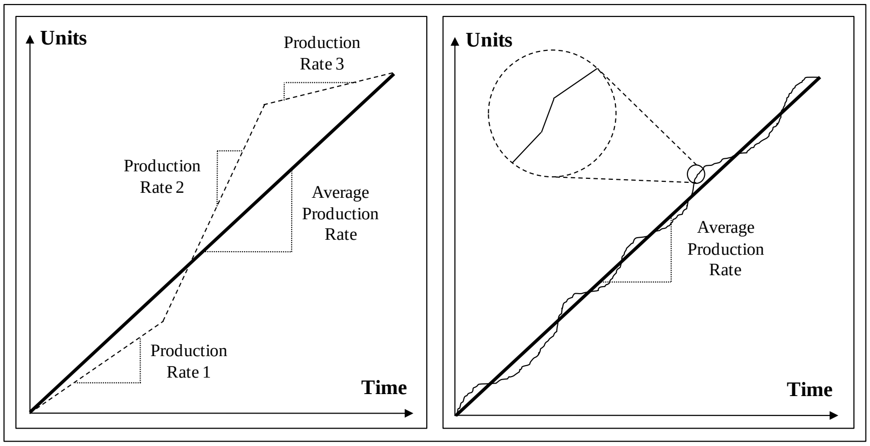

Fig. 2. Production Rate diagrams considering variability, which can be generating through simulations.

The other important steps in linear scheduling deal with identifying conflicts (which have to be avoided), and buffers (Work-In-Process (WIP) buffers and Time buffers, which have to be used to deal with conflicts) (Fig. 3).

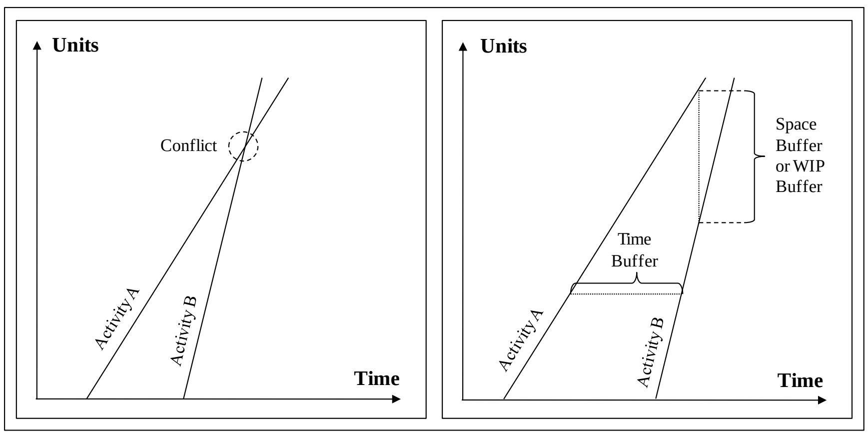

Fig. 3. Conflicts and WIP buffer and Time buffer (adapted from Hinze, 2007).

As a result, the idea behind bringing together linear scheduling techniques and simulation is to graphically represent the progress of a project (linear scheduling), but considering the effect of variability on production rates (simulation). Figure 4 schematically shows a linear project where activities (or processes) take into account variability. It could be recalled that for transportation construction projects, these linear activities can be: clearing, road preparation (grading, subbase, base coarse, etc.), paving, etc. (Callahan et al., 2002).

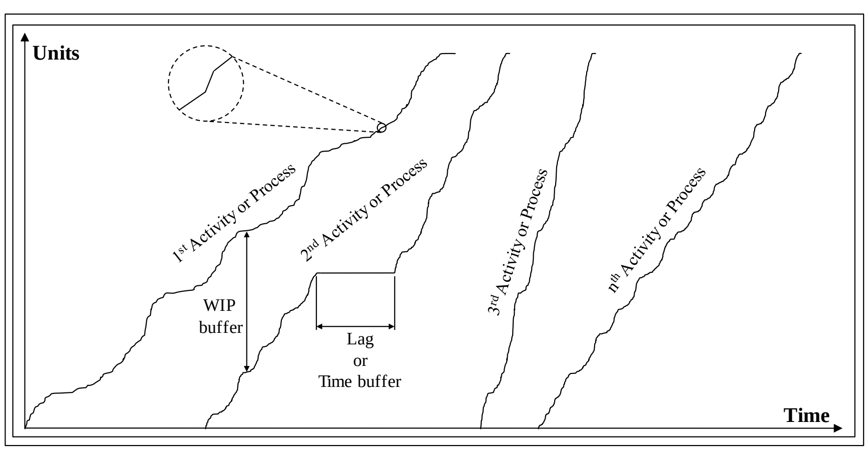

Fig. 4. Linear scheduling considering the effect of variability.

3.2. Selection of activities to be included in the simulation model

After explaining how linear scheduling techniques work and showing that linear activities are feasible to be scheduled considering variability, it is necessary to focus on what activities, within a highway construction project, should be included in the simulation model.

In the US, most of the Departments of Transportation establish a set of activities which have to be considered as a basis for pay items in transportation construction projects. For example, the Florida Department of Transportation (FDOT) defines almost six hundred activities which can be part of a transportation project (FDOT, 2010). In order to determine the main activities involved in transportation construction projects, data from an actual project in the State of Florida is presented in Table 1 as an example.

The categorization shown in Table 1 has been done according to the following criteria: 1) Type of activity; 2) Percentage of cost for the set of activities in relation to the total cost of the project (activities selected, grouped by categories, represent more than the 80% of the total cost of each project) and; 3) Activities which historically have lead to delays during the construction phase of highway projects.

The first criterion "Type of activity" relates to the scheduling method to be used (in this case, linear scheduling). This means that activities have to be suitable to be scheduled according to the linear scheduling principles seen in the preceding section. The second criterion "The cost of activities over the Total Cost" relates to the Pareto Law or 80/20 rule, which states that approximately the 80% of a system is represented by the 20% of it (Chen et al., 1993); i.e., the 80% of the total cost of a project is concentrated in just a 20% of its activities. The third and final criterion "Activities which lead to delays during the construction phase" relates to identifying those activities which historically have produced delays according to the review of literature (Thomas and Ellis, 2001).

Six categories have been found relevant for a transportation construction project: Maintenance of Traffic, Road Preparation/Earthwork, Drainage Works, Asphalt Pavement, Permanent Signaling, and Erosion Control. These six categories of activities were chosen according to how these categories affect the project in terms of budget and schedule. Based on the example given in Table 1, it was found that the selected categories represent an 84.88% of the total cost of the project. On the other hand, in terms of scheduling, these 6 categories showed to have a linear behavior; as a result, they were chosen to be included in the model.

As an additional source to support the previously-mentioned selection of categories, Maintenance of Traffic and Utilities (in this research, Utilities is partially characterized by Drainage Works) are categories of activities that have been identified as root causes of delay on highway projects (Thomas and Ellis, 2001). In turn, Earthmoving (in this research, characterized by Road Preparation) and Pavement (Asphalt) represent a very important part of a highway project's construction time and money expenditures (O'connor et al., 1993). In summary, the activities shown in Table 1 represent the categories which involve the main activities within a transportation construction project.

Table 1. Categories of main activities of a transportation construction project

ID	Category	% of Total Cost	Observation
1	Maintenance of Traffic	10.00 %	Temporary barriers, signals, maintenance of traffic operations.
2	Erosion Control	1.00%	Silt fences, hay bales, erosion barriers, rip raps.
3	Drainage Works	24.54 %	Construction of culverts, drains, manholes, curbs and gutters, etc.
4	Road Preparation/Earthwork	18.71 %	Removal of existing pavement, excavation and base layers.
5	Asphalt Pavement	15.54 %	Asphalt pavement layers, bituminous materials, joints sealing.
6	Permanent Signaling	15.09 %	Speed signals, traffic stripes, pedestrian signals, traffic controls.
	Total Percentage	84.88%	

3.3. Method for the unification of multiple contract pay items

Because of the daily progress of the activities is commonly measured by different units (cubic yards, square foot, miles, etc.), according to diverse contract pay items defined by diverse Departments of Transportation, such as the FDOT (FDOT, 2010), a unified numerical value is needed to calculate the productivity per project, in order to be able to group and add various pay items into categories. Also, this is necessary to make possible the scatterplot of the progress chart of these activities in a uniform scale of production units against time. Lee (2003) developed a methodology for unifying the productivity on highway construction by using an Equivalent Work Unit (EQWU), which corresponds to the equivalent amount of work that can be accomplished with eight man-hours of effort. This method for unifying the productivity on highway construction projects is adopted as a part of the conceptual methodology presented in this paper to deal with the negative effects of variability in transportation construction projects.

3.4. Selection of proper buffers to be used in the model

Hopp and Spearman (2000) establish three types of buffers in production systems: Inventory buffer, Capacity buffer and Time buffer. These buffers can be classified as: Inventory buffers, mainly characterized by raw materials, Work-In-Process (WIP) and finished goods; Capacity buffers, characterized by redundant labor (which can be separated into workers and machines); and Time buffers, with the main objective of managing production schedules and deliveries on due dates (Hauge and Paige, 2002).

In construction, buffering strategies have been applied during almost twenty years and they are summarized in Table 2 (González et al., 2006).

Table 2. Buffering Strategies used in Construction (adapted from González et al., 2006)

Research/Approach	Research Strategy	Type of Buffer
Lean Construction	Monte Carlo simulation; Simulation Optimization; dynamic simulation; others.	WIP Inventory
Lean Construction; Supply Chain Management	Discrete Simulation; Application of Kanban System; Cumulative progress of processes; value stream mapping.	Material Inventory
Lean Construction;	Monte Carlo simulation	Capacity
Lean Construction; Supply Chain Management	Fuzzy Logic; Dynamic Simulation; Simulation Optimization	Time
Lean Construction; Supply Chain Management	Discrete Simulation; Processes diagram flow.	WIP Inventory; Material Inventory; Capacity

Table 2 shows that WIP, Material, Capacity and Time buffers have been broadly used within the construction industry. However, for purposes of programming the model, time buffer has been treated in terms of Work-In-Process, i.e. WIP buffer. In addition, regarding with WIP buffers, Ashley and Alarcón (1999) observed that a loss of productivity can be because the work-units to perform by production process are not enough, which emphasize the importance of WIP buffers.

In terms of the project duration, the National Cooperative Highway Research Program (NCHRP) determined and ranked the main factors affecting time determination (NCHRP, 1995), which are summarized in Table 3.

Table 3. Factors Affecting Time Determinations and Buffers (adapted from NCHRP, 1995).

Ranking	Factor	Type of Buffer
1	Weather and Seasonal Effects	WIP
2	Location of Project	Material/WIP
3	Traffic Impacts	WIP
4	Relocation of Construction Utilities	WIP

On the other hand, Thomas and Ellis (2001) observed that the leading apparent causes of delay to highway construction projects were those shown in Table 4.

Table 4. Apparent causes of delay to highway construction projects (adapted from Thomas and Ellis, 2001).

Causes	Type of Buffer
Utilities	WIP
Delays in environmental planning and permitting issues	WIP
Differing site conditions	WIP
Errors and omissions	WIP
Extra work	WIP / Capacity

According to Tables 3 and 4, WIP, Material and Capacity buffers seem to be the most recurrent in transportation construction projects. Also, Thomas et al. (2003) focused their attention on labor (capacity), emphasizing the fact that manpower vary throughout the course of a project. On the other hand, complementing the previous findings, O'Connor (1993) had already found that differing site conditions, constructive changes, errors and omissions and weather (all related to WIP buffers), represented some of the most common causes of conflicts and claims within a transportation construction project.

Moreover, Agdas (2008) emphasizes the idea of materials as scarce resources within transportation construction projects, particularly when those materials are not easily available (e.g. location). That highlights the importance of considering the buffer material as shown in Table 3.

As a conclusion, taking into account the types of activities which more influence delays in transportation construction projects and the buffering strategies previously applied to other types of projects, the buffers to be used in the proposed model will be: Work-In-Process, material and capacity (classified into worker buffer and machine buffer).

3.5. Conceptual Methodology proposed

This paper has been devoted to propose a methodology to deal with the negative impact of variability in transportation construction projects, through the use of buffers. Based on the previous steps, some guidance is proposed to build simulation models that can help deal with variability and its effects on transportation construction projects.

The conceptual methodology presented here will be organized through a flowchart with the main steps to be considered at the moment of elaborating a simulation model of a transportation construction project. The flowchart is shown in Figure 5.

Flowchart in Figure 5 starts with the selection of activities to be included in the model, accounting for those activities which concentrate at least an 80% of the total cost of the project. This task is not necessarily tedious because, according to the 80/20 rule or Pareto Principle (Chen et al., 1993), it is only required to focus on the 20% of the main activities of a project which will accumulate the 80% of the total cost of it. The following step is to figure out if the selected activities are suitable to be linearly scheduled (i.e. activities where linear scheduling techniques can be applied). If this condition is not accomplished, it is necessary to leave the process and search for another methodology to simulate the project. Then, the selected activities have to be grouped in just a few categories in order to facilitate the programming of the model (no more than 10 categories, e.g. Maintenance of Traffic, Road Preparation, Asphalt works, etc.). With the same objective of facilitating the implementation of the model, this methodology suggests to use only one measurement unit according to what is suggested by linear scheduling techniques (miles, yards, etc. or another equivalent working units). Subsequently, the project has to be linearly scheduled using the categories previously defined in the preceding step, constituting the deterministic approach which will be compared against the simulation-based model (probabilistic/simulation approach). As a key part of the simulation-based model, it is necessary to determine the probability distribution functions that govern the duration of each category of activities (this is done using actual/on-site information and running multiple goodness-of-fit tests). The following step is the selection of the buffers to be used in the model (first, all buffers are included and after the first loop the buffers are selected according to the analysis run at the end of this methodology). Then, the conceptual model is designed (probabilistic/simulation approach), laying the foundation of the simulation model to be programmed later. After programming the simulation model, a comparison between the deterministic approach and the simulation-based approach is conducted; if the outputs from both approaches are comparable the process continues, if not, the process is stopped and it is necessary to go two steps back to the selection of buffers and the development of the simulation model. As mentioned, if the outputs are comparable between both approaches (deterministic and probabilistic), it is then necessary to validate the simulation-based outputs through the run of Analyses of Variance and Multivariate Analyses of Variance, validating or not the proposed buffers. If the proposed buffers are not validated for the ANOVA and MANOVA tests, it is necessary to drop the buffers which are not appropriate and to go back to the selection of buffer step. On the contrary, if the proposed buffers are validated, the whole process ends with the utilization of the output information (simulation-based approach), as a tool to make better decisions in order to minimize the impact of variability in transportation construction projects.

Therefore, aiming to mitigate the negative effect of variability, the preceding methodology offers conceptual guidance to model a transportation construction project, through the use of linear scheduling theory in combination with simulation techniques and buffering strategies. Even more, despite the fact that the model presented in this paper has been developed through the use of a specific software package (ExtendSim, 2008); it is perfectly feasible to expand this conceptual methodology to the use of any other simulation software, even Excel combined with Crystal Ball (2010).

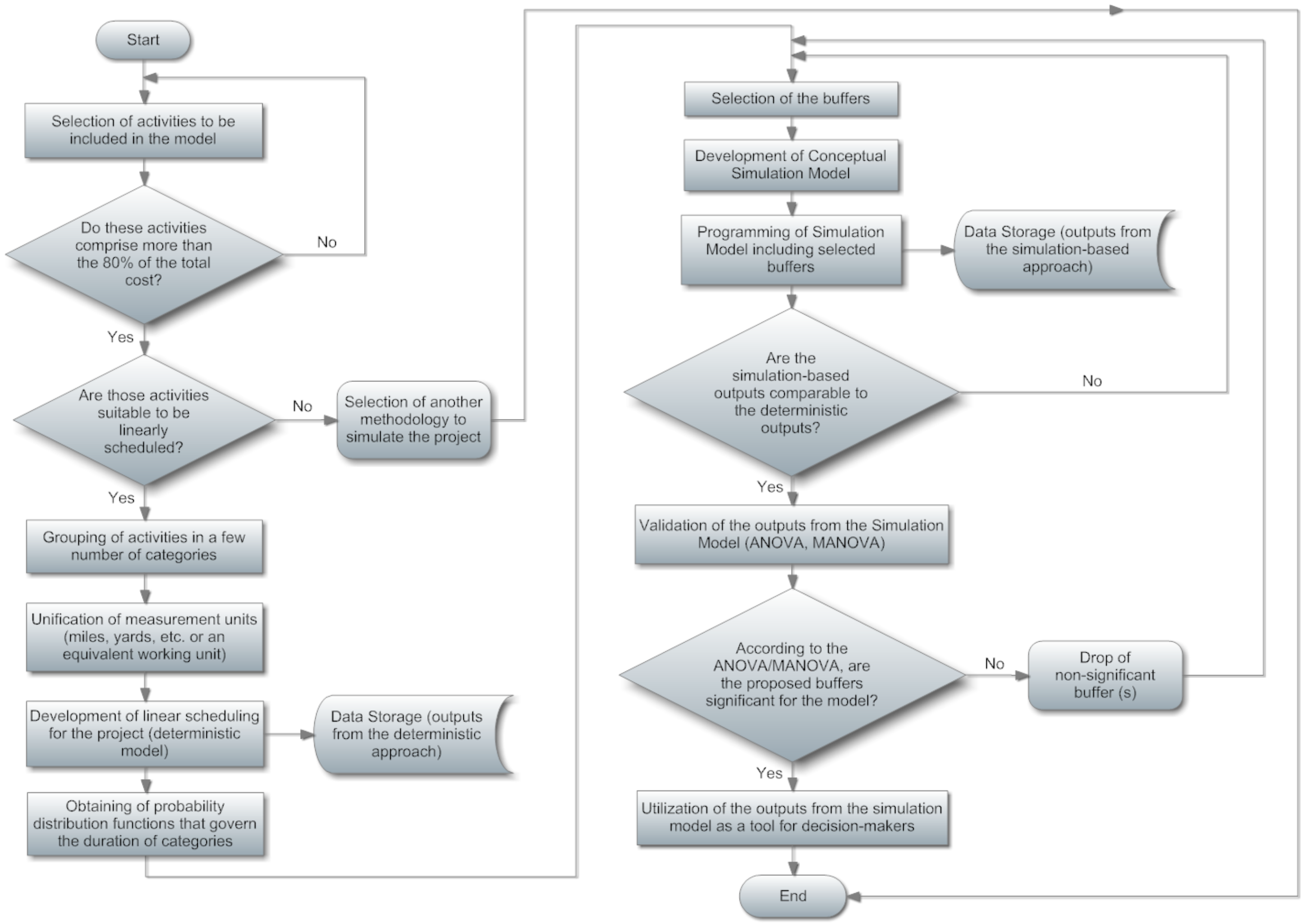

Fig. 5. Flowchart of the conceptual methodology.

4. CONCLUSIONS

This paper was focused on proposing and testing a simple graphical approach based on simulation techniques and buffering strategies applied to transportation construction projects and, more generally, proposing a conceptual methodology to build simulation-based models that help deal with the negative impact of variability on this type of projects.

This conceptual methodology allows the researcher to develop a simulation-based model for any type of transportation construction project, with the final and most appreciated objective of utilizing the outputs of the model as a tool for decision-makers. This methodology permits to select the appropriate activities to be included in the model, to select the buffers, to compare the outputs given by the model with actual data, to determine whether the buffers are statistically significant (ANOVA, MANOVA) and, if not, to loop back to previous steps to feedback the model with the relevant buffers found, finishing the process with the utilization of the outputs information in order to make better decisions.

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