AUTOMATING ROAD CONSTRUCTION PLANNING WITH A SPECIFIC-DOMAIN SIMULATION SYSTEM

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SUMMARY: Road construction projects are very expensive, unpredictable and highly influenced by unpredictable factors, like weather, type of soil, environmental issues, and other factors. This has led to difficulties in developing accurate construction plans and modelling the construction operation using a traditional simulation system. In this context, the aim of this research is to create a knowledge driven road construction simulation system to assist project managers in generating accurate and reliable road construction plans.

Road construction operations and rules governing the actions and interactions of the resources have been identified, developed, classified and modelled through a comprehensive analysis of 145 road construction projects. For every road construction operation (activity) a computer-based template for atomic models was defined and developed. The models encapsulate productivity equations and factors influencing the productivity of resources and automating the scheduling of works. Also, the models provide a means for evaluating several resource allocation alternatives under a wide range of scenarios.

A real life case study was modelled to identify applicability, accuracy and usefulness of the developed simulation system and results are presented in this paper. The study concluded that the system generated fast and accurate productivity and unit cost of road activities to develop a construction schedule of the road construction project.

KEYWORDS: Simulation, Road construction, Knowledge base, Productivity, Case study

1. INTRODUCTION

Current practices in the road construction industry suggested that planning and scheduling in road construction is inefficient and projects are often over budget and over time (Castro et al, 2005). Also, project managers use only their experiences, historical and technical data and gut feeling to plan and manage the process. In order to have efficiency gains and construct projects on time and on budget, more innovative tools and techniques are needed to assist managers in planning and managing road construction projects. Also, there is a need for tools that will be able to assist project managers to study and compare all possible strategies and methodologies for the execution of the works and without this comparison there is will be no evidence that the planner's choice corresponds to the most advantageous possibility.

The idea that innovation in construction should go beyond the boundaries of the products and construction processes and reach the organisational structure, management techniques and business models of the construction companies (Hitt et al, 2001) is commonly accepted as being correct. However and despite all the potential benefits and value offered by innovative management techniques, various researchers have concluded that systems related to the planning of construction projects and using simulation modelling and visualisation, have had a limited penetration in the construction industry (Kamat and Martinez, 2001; Hajar and AbouRizk, 2001). Researchers have also concluded that the major drawbacks for the use of simulation systems in construction planning are the fact that (i) most of the IT or other innovative solutions have not been tailored to fit the project manager's requirements (Gann and Salter, 2000); (ii) the long-term expectation requirements for the IT tools are in conflict with the traditional short-term project based assessment of the results in the industry (Pries and Janszen, 1995) and (iii) the investment required for the acquisition of the systems is high, the learning effort and time to build the simulation models are considerable (AbouRizk and Mather, 2000).

The fact that most of the simulation systems are implementations of the concept of the CYCLONE system developed by (Halpin, 1973) are general purpose and mostly network based, may be the explanation for the limited penetration of simulation in construction planning. RISim, a general-purpose simulation system (Chau and Li, 2001), considers construction resources as objects and the interactions between resources as the operation logic. There are two abstraction levels in RISim: one referring to the resource level and the second to the process level. The resource level deals with resources and their relationship, while the process level deals with construction activities. Logic is associated to each process (activity) to describe the actions taken in the construction process. KMOS (Kim and Gibson, 2002) was presented as interactive simulation modelling oriented for heavy construction operations. The system shares both resource and process-oriented characteristics. The system allows for modularised simulation model building and provides step-by-step guidance in model building.

AbouRizk and Mather, (2000) developed a simulation system through integration with 3D CAD in which each resource is associated with its "atomic model". The concept of "atomic model" has been presented by Ziegler (1987), Luna (1992) and Odeh (1992) in order to simplify simulation model building.

In all the mentioned simulation systems the model should be built every time the simulation is required and this may be tedious and time-consuming. Moreover, the general-purpose characteristics of those systems reduce their simplicity and applicability. Also, these simulation models are 'number crunching' machines and lack 'intelligence' which can be essential if a practical real life situation is to be modelled. Other simulation systems include visualisation of the construction process, i.e. provide visual understanding of the construction process, either in terms of the physical aspect or in terms of the sequence of execution (Op Bosch, 1994). In these types of systems can be included a methodology proposed by (McKinney and Fischer, 1998) for the generation, evaluation and visualisation of construction schedules using a 4D CAD. VIRCON is another 4D modelling system allowing the elaboration of the tradeoffs between the sequencing of the works and respective spatial distribution (Dawood et al, 2004 and Winch, 2002).

One of the major conclusions that the authors have reached in reviewing historical and recent literature is that there is very little work that has been undertaken in the simulation of road construction. No paper was found dealing with road construction as a whole process, composed by tasks defined as "plan the project", "execute the works" and "evaluate the economic results". The difficulty faced by the researchers is probably due to the fact that road construction is difficult to model and simulate and has a particular culture for planning and performance management. This has been influenced by the following distinct road construction risk factors:

- The geographical extension of the works;
- The sensitivity of the road works to the local conditions (materials to be removed, water table, site organisation, accesses, etc.);
- The sensitivity of road works to the weather conditions;
- The environmental impacts;
- The potential conflicts with other social and economic activities

To overcome issues associated with previous research models and introduce simplicity, knowledge and specificity into a simulation system, this paper discusses a modular approach that was implemented using integration of common MS Windows commercial software packages like spreadsheets, databases and MS Project. The proposed simulation system dubbed "RoadSim" is based on a modular approach known as the "atomic model" introduced by (Ziegler, 1987) and used by (Luna, 1992) and (Odeh, 1992). The main principle of the atomic model depends on the possibility to break down a complex system like road construction into several sub systems of lesser complexity. The final sub system is a module or atomic model. For example, an atomic model of a tipper truck can be used in all activities that include "loading and hauling", such as cut to fill,

cut to spoil, sub base execution; bituminous mixes production and placing. The following section details the principles of 'RoadSim' and development processes.

2. ROADSIM PRINCIPLES

Road construction is basically an equipment-intensive process and therefore is ideal for simulation since the activity of an equipment unit is repetitive and can be considered as partially self-controlled and influenced only by the respective working conditions (Castro and Dawood, 2005).

The main principle that underpins the concept of RoadSim was the possibility to break down a complex system like road construction into several sub-systems of lesser complexity. The process of division continues until the simplest indivisible entity is found. This final sub-system is a module or atomic model, as shown in Figure 1.
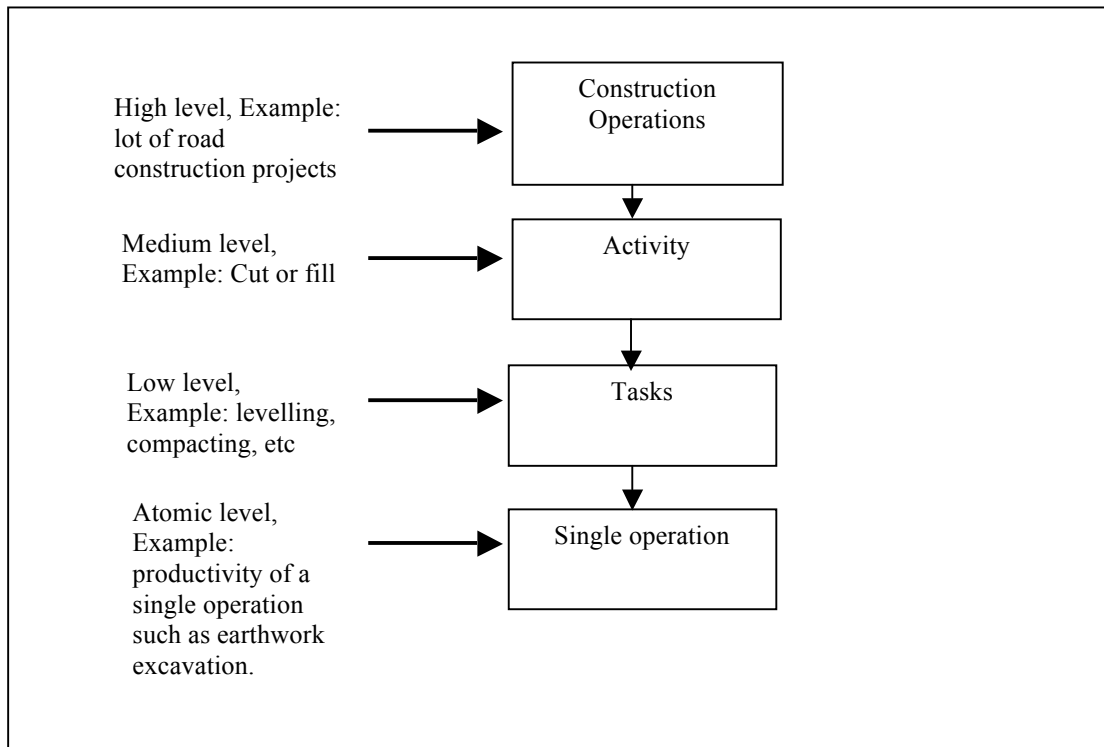
FIG. 1: Breakdown of road construction operations

A complex construction operation is the aggregation of very small modules or atomic models. Once these atomic models are developed, any construction operation can be modelled by coupling the "atoms" that constitute the "substance". For example, the process of the tipper truck activity shown in Figure 2 is always the same, the differences being the results of the interactions with other resources working in the same activity (type of loader, number of trucks, etc.) and the interactions with the actual working conditions like technical specifications, hauling distances, type of access, availability of space for manoeuvring, etc.
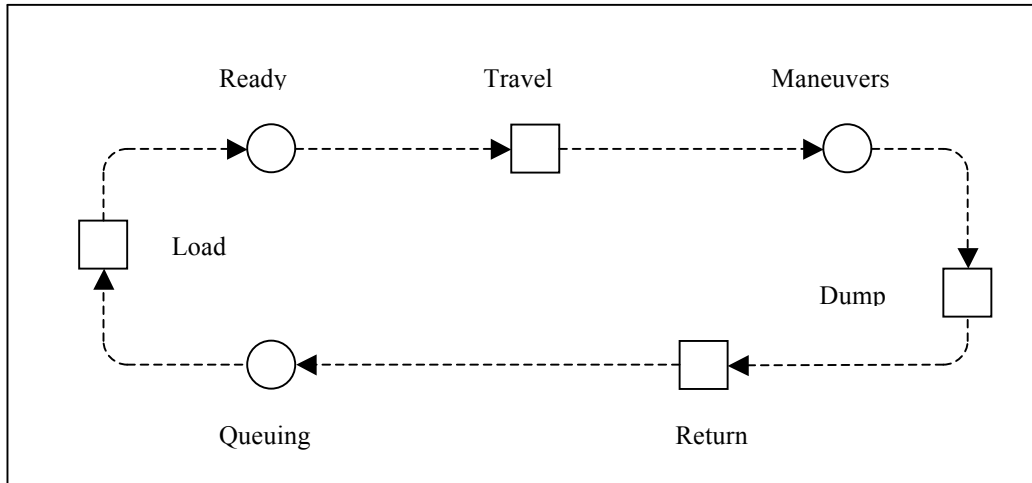
Indicates idle state of tipper truck ◯

Normal working state of tipper truck ☐

FIG. 2: Atomic model of Tipper Truck for loading and hauling activity.

For the tipper truck, several events can be identified as indicated in Table 1. In this example, it can be seen that the modelling can be done by tracking certain variables such as, time elapsed, state of the system at the time "t", etc. Table 1 refers to the action of a single resource and is the lowest level of the action of the tipper truck. Hence the term *atomic model* describes the process involved.

TABLE 1: Events in tipper truck activity

Time	T1	T2	T3	T4	T5	T6	T7
Event	Arrival	Loading	Travel loaded	Manoeuvre	Dumping	Travel empty	Queuing

Theoretically it is possible to continue breaking the action of the tipper truck into smaller parcels like "manoeuvring" or "dumping" (that can be considered the "electrons" and "neutrons" of the atom). However, this might not be useful in the practical real world, though that reasoning may be used for the definition of the cycle time. In the case of the tipper truck action, the cycle time will be always the result of the aggregation of the times of all parcels ("electrons") that compose the atomic model (time of "loading", time of "dumping", time of "hauling loaded", etc.).

If more than one resource is involved in a concurrent action, the process can also be modelled in the same way, as occurs with the modelling of the pay loader and tipper truck indicated in Table 2.

TABLE 2: Loading operation modelling

Loader	Time	T11	T21	T31	T41	T51	T61	T71	
	Events	Travel frontward (A)	Load bucket	Travel backward (A)	Manoeuvre	Travel frontward (B)	Load truck	Travel backward (B)	
Truck	Time	T12	T22	T32	T42	T52	T62	T72	T82
	Events	Arrival	Start load	End load	Travel loaded	Manoeuvre	Dump	Return	Queuing
					Tipper truck routine				

Whereas A indicates operation at loading place and B indicates at dumping or spoiling sites

Table 2 contains two atomic models, pertaining to the tipper truck and pay loader, respectively. The modelling of the combination of the two resources cannot be the simple addition of the two atomic models since Table 2 does not depict the problems that may arise with the interactions of the resources. To show the interactions properly, a flowchart is required. Figure 3 shows a flowchart referring to the combined actions of the tipper truck and pay loader and problems related with queues can be highlighted in the flow chart. The actual performance of combining atomic models will be influenced by a wide range of risk factors which influence productivity and cost. This paper develops an empirical approach backed by knowledge generated from analysis and knowledge elicitation of historical projects to assess the impact of a wide range of risk factors and encapsulate this in 'RoadSim' as given in the following example.
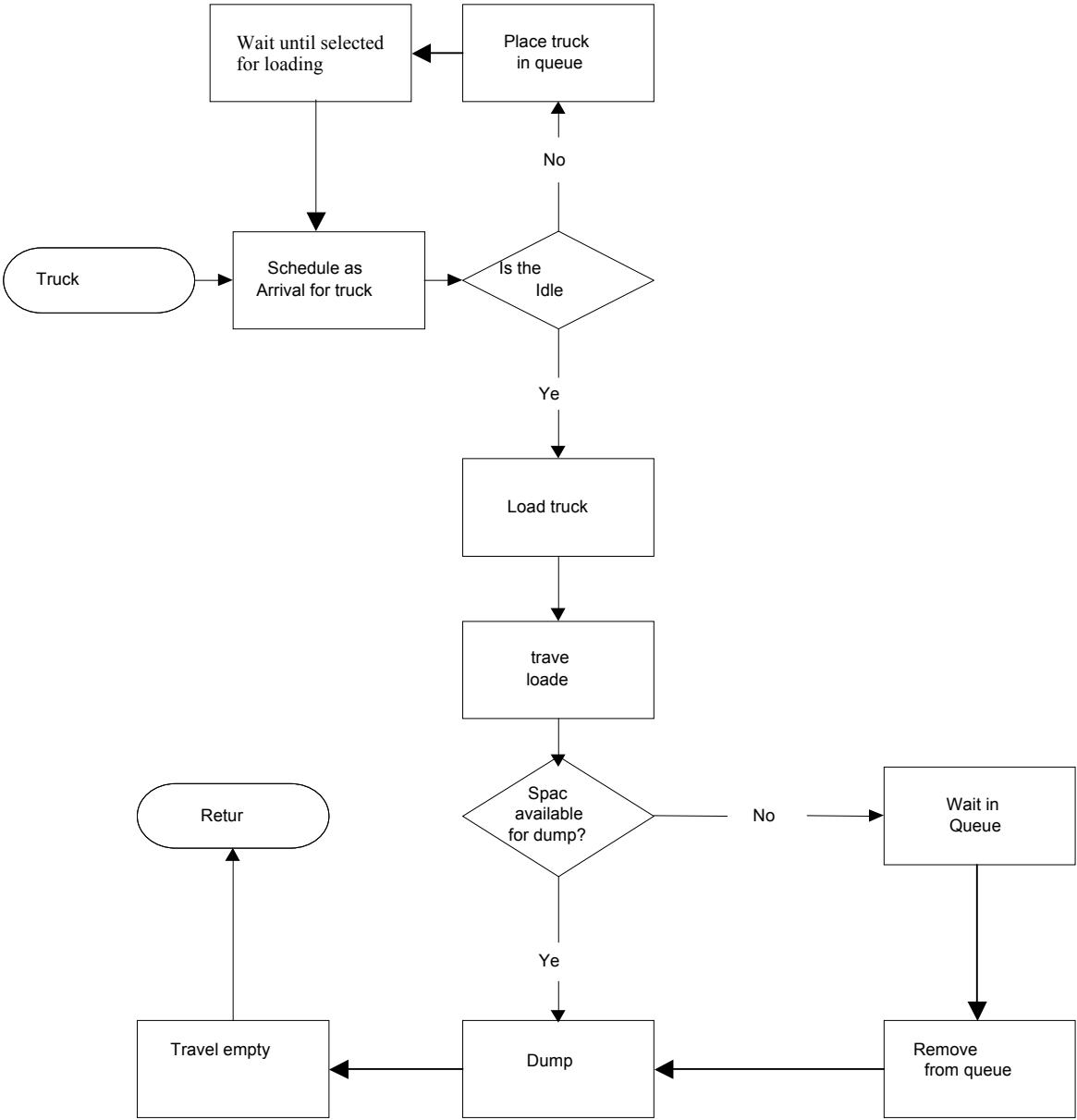
FIG. 3: Tipper truck/loader activity flow chart.

As an example, the performance of the activity of the tipper truck depicted in Figure 2 is a result of the integration of the inherent characteristics of the machine (power engine, bucket capacity, etc.) with the interactions introduced into the construction process by the working conditions. But the tipper truck always performs the same sequence of actions: loads, travels loaded, dumps and returns to the loading point. That is the atomic model. The differentiation will be introduced by the actual working conditions: type of access, hauling distance, type of material loaded, number of trucks in the operation, availability of space at the dumping area, size of the loader, skill of the driver, site organisation, etc.

Therefore, the action of a resource can be defined as given in Eq. (1)

$$A = A_m * W_c \text{---} \tag{1}$$

In which,

A = Productivity of an active task;

A_m = Atomic model (basic productivity of an activity);

W_c = Factor referring to working conditions.

As the atomic model is immutable for a given resource, the A_m can be used in different construction activities. For example, the atomic model of a tipper truck can be used in all activities including "loading and hauling", such as cut to fill, cut to spoil, stone base or sub-base execution, bituminous mixes production and placing, chemically stabilised layers, etc.

In this way, the atomic model can be seen as a "module" capable of being used in different activities or construction operations. This modularity leads to the establishment of a concept that can be presented by Eq. (2)

$$A_T = \sum (A_{mi} * W_{ci}) \text{----------------------------------} \tag{2}$$

In which

A_T = Total productivity of a given activity

A_{mi} = Atomic models of the resources intervening in the activity (productivity);

W_{ci} = Working conditions influencing each resource action.

Using the defined concept, the modelling of an activity is always performed through following steps:

   a. Definition of the resources that will be used in the execution of the different tasks composing the activity;

   b. Definition of the atomic models of every resources used;

   c. Definition of the working conditions affecting the performance of each resource;

   d. Coupling of the atomic models that are already affected by the working conditions.

In the case of RoadSim these parameters have been defined through a knowledge acquisition process which is given in the following section.

3. KNOWLEDGE ACQUISITION PROCESS

The identification and definition of the influence of the working conditions on performance of a resource or construction system can only be achieved through a detailed analysis of the outcomes of real life road construction projects carried out previously. The influence of the working conditions are risk factors that practitioners have responded to by establishing practical and judgemental rules to take into account the respective consequences. In order to obtain the expert rules concerning road construction, a knowledge acquisition process was undertaken, aimed at the identification of activities and resources included in road construction projects, alternative construction methods as well as the influence of the working conditions on the performance of such resources. In order to achieve this, 145 previous road construction projects in Portugal have been analysed thoroughly. The value of each project varies from 8 to 53 million Euros. For the definition of the activities that constitute "a typical road project" the authors analysed the Bill of Quantity (BOQ) of all projects. The activities have been grouped into three categories "earthworks", "drainage" and "pavement" and the activities that have a frequency of more than 50% in all BOQ for the 145 projects were included in the analyses. Alongside historical information, the authors used equipment and machinery manufacturers' information for the definition of the equipment used in road construction, respective productivity and determination of the effect of the working conditions. The first step in the construction site knowledge acquisition process was the definition and analyses of construction activities, basic package of equipment units, materials and labour. Also, the analyses yield the definition of the rules governing the actions and interactions between resources and working conditions in road construction.

In the second step, 50 basic road construction activities were identified and the respective alternative methods of construction were identified. A list of the activities will be shown in the case study. As an example, Table 3 shows the different methods of performing earthworks, corresponding basically to using different combinations

of equipment units to execute the works. Note that independently of the size or objective of the road, earthworks in road construction are always an association / aggregation of the following activities:

(Cut + hauling + dump + levelling + watering + compaction)

The same exercise was performed for other identified activities.

TABLE 3: Earthworks activities and corresponding tasks

Activity	Execution Method	Tasks (by resources)
Cut	Method 1	Dozing + pay loader
	Method 2	Excavator
	Method 3	Pusher + motor scraper
Haul / dump	Method 1	Tipper truck
	Method 2	Dumper
	Method 3	Motor scraper
Levelling	Method 1	Motor grader
	Method 2	Bulldozer (mass earthworks)
Watering		Water tanker
Compaction	Method 1	Vibrating roller
	Method 2	Sheep foot roller
	Method 3	Pneumatic roller

The determination of the productivities of the atomic models considered necessary for the modelling of the totality of the road construction domain was obtained from the analysis of historical data of 145 projects that were constructed in Portugal. This productivity data was then grouped according to the conditions under which projects were constructed. In this case, parameters referring to the working conditions have been established and linked to productivities of atomic models, namely those concerned with the "site organisation", "job efficiency", "type of accesses", "queue effect", "random works", etc.

By capturing professional knowledge, historical records and manufacturer's information, a basic package of equipment used in road construction was defined, taking advantage of the fact that manufacturers tend to produce similar types (capacity and functioning) of equipment units. For the identified units it was observed that some associations of equipment could be defined, meaning that some types are "forced" to work in a sort of partnership with others. For example, a motor scraper never interacts with a tipper truck, since the scraper has been designed to work and interact with a bulldozer (pusher) at the loading point and with a bulldozer or motor grader at the dumping point. The possible associations are shown in Table 4. The identification of these associations is important since it allows the study of possible interactions between different equipment partners and their related capacities.

TABLE 4: Association of equipment resources in road construction

RESOURCE	EQUIPMENT PARTNER
Bulldozer	Pay loader
	Motor grader
	Roller
Motor scraper	Bulldozer
	Motor grader
Pay Loader	Bulldozer
	Tipper truck
	Dumper
Excavator	Tipper Truck
	Dumper

Motor Grader	Tipper truck
	Dumper
	Motor scraper
	Roller
	Water tanker
Tipper truck	Excavator
	Pay loader
	Asphalt plant
	Concrete plant
	Crane
	Motor grader
	Asphalt paver
	Slip form paver
Dumper	Motor grader
	Excavator
	Pay loader

With regards to the working conditions and interactions, the same reasoning and procedures were adopted in order to obtain the identification and definition of the influence of the respective factors. Numerical coefficients have been attributed to each factor, therefore allowing the determination of the real productivity of the resources performing an activity in the following equation:

$$P = P_b * w_1 * w_2 * w_3 \text{-----------------------}$$ (3)

In which,

P = Real productivity of the considered resource – m^3/hr;

P_b = Productivity of the atomic model – m^3/hr;

W_1 = Factor referring to the working conditions;

W_2 = Parameter referring to the interactions with the "partner" resource;

W_3 = Parameter related with the random works of possible execution during the construction process.

With this information, empirical equations have been defined for the determination of the productivities of every resource in a given activity. Eventually, all of the processes were summarised graphically as the example shown in Figure 4, which represents the actions and interactions of a motor scraper and bulldozer in the push and load task.
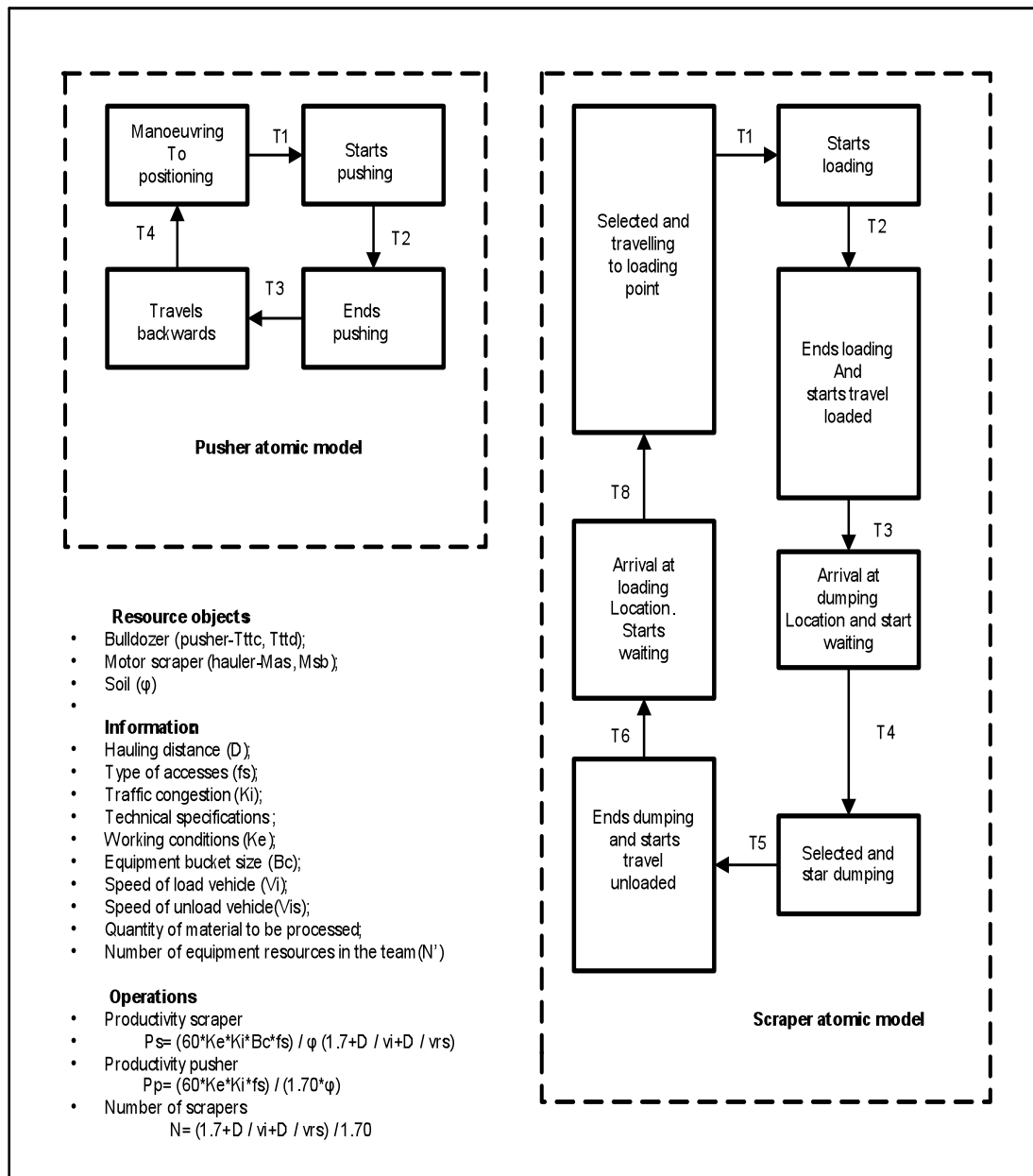
FIG. 4: Example of a module concerning a pusher-motor scraper activity

Hundreds of productivity empirical equations, an example shown in Figure 4 have been developed and used to populate a database that is the core infrastructure of the simulation system. Figure 4 will be further elaborated in section 5.

4. IMPLEMENTING A ROAD CONSTRUCTION-ORIENTED SIMULATION SYSTEM

RoadSim has been developed to mimic the way in which road construction planners develop construction plans. The main processes of RoadSim are: determination of near optimum cost and time of road activities, identification of the most productive resource combinations and production of a schedule that meets the clients and company requirements. The main inputs to RoadSim are: bill of quantities, technical specification of resources and working conditions.

The simulation system was implemented using the architecture shown in Figure 5. At the heart of the system is a relational database which holds productivities of different resource combinations and information about previous projects which include activities, resource attributes and productivity factors. The database contains all atomic

models and modules for modelling the most common road construction operations. The coupling of these atomic models is performed automatically by the system.
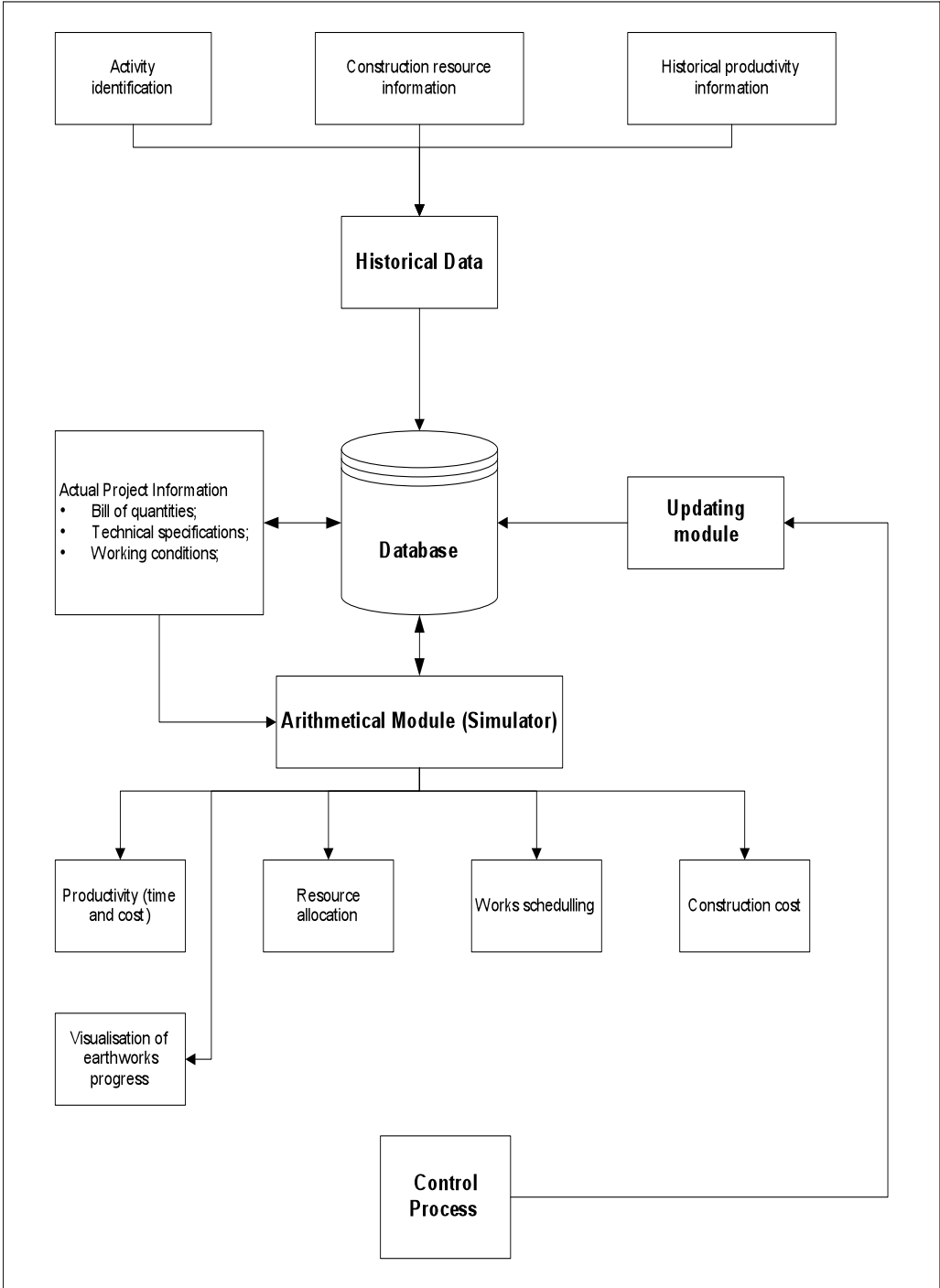
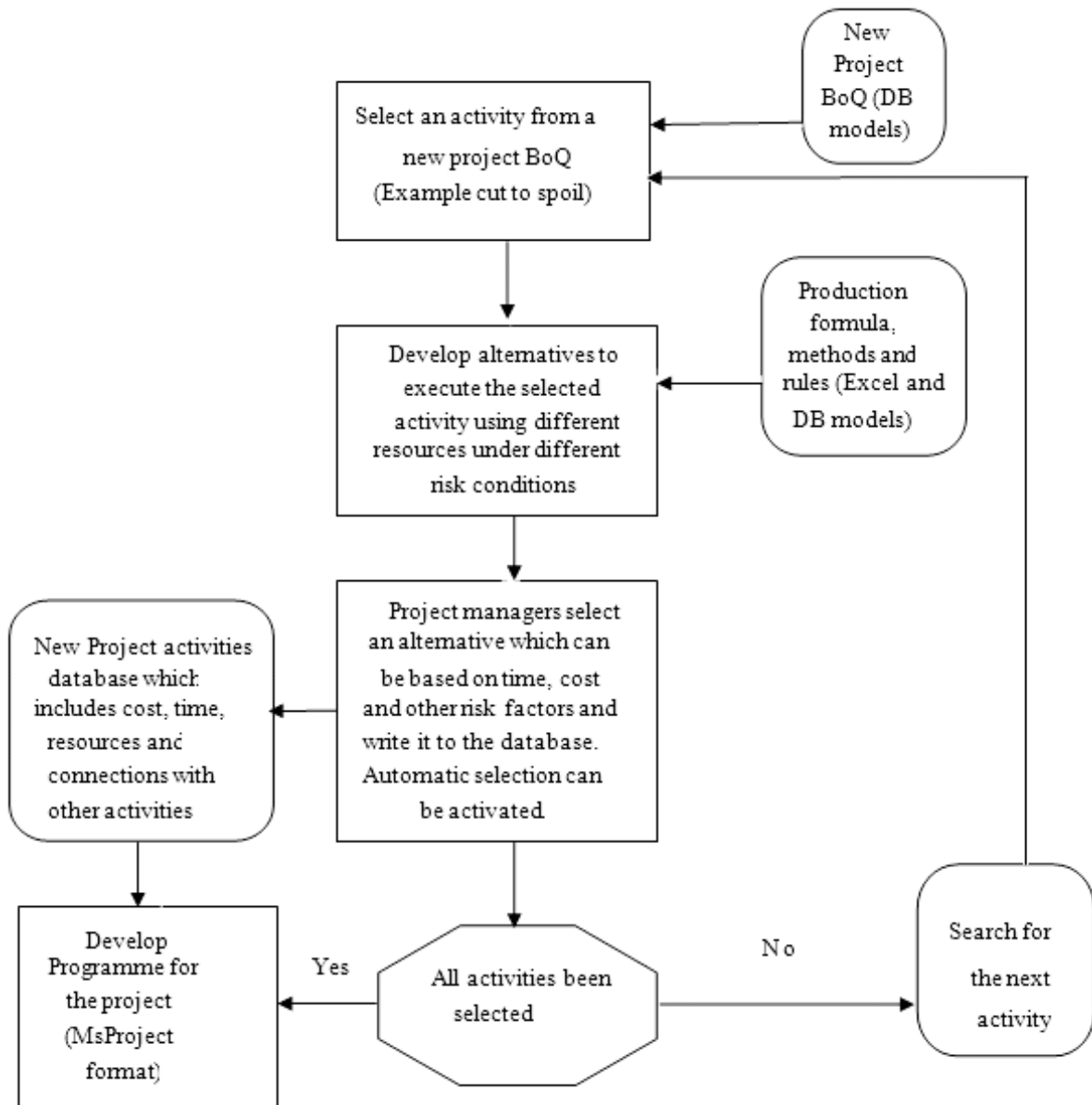

FIG. 5: RoadSim system architecture

Select an activity from a new project BoQ (Example cut to spoil)

New Project BoQ (DB models)

Develop alternatives to execute the selected activity using different resources under different risk conditions

Production formula, methods and rules (Excel and DB models)

New Project activities database which includes cost, time, resources and connections with other activities

Project managers select an alternative which can be based on time, cost and other risk factors and write it to the database. Automatic selection can be activated.

Develop Programme for the project (MsProject format)

Yes

All activities been selected

No

Search for the next activity

FIG. 6: RoadSim software process flowchart

The system was designed to allow updating and customisation to the specific situation of the user. For example adding more resources, updating formula to conform to specific conditions of risk factors (weather, type of soil, terrain conditions etc). Figure 6 shows the flow chart of the model. The flow chart is self explanatory and the main processes are:

- Selecting road activities of a new project from a database which includes standard naming of activity and quantities. Table 5 shows a case study example of BOQ which include activities, units and quantities. The example given will be discussed further in the case study section.

- Develop alternatives for each activity in terms of time and cost under different conditions and resource allocations. As given in Table 3, for each activity there might be a number of construction methods and different combinations of resources. This was identified from knowledge elicitation of previous projects discussed earlier in this paper. To calculate productivity, users input the actual working conditions affecting every atomic model. For example and referring to the excavator, the user should input:
    o Type of excavator: the menu offers 4 options and the planner should select the type that is going to be used in the project;

- o Rotation angle: according to the site conditions, the menu offers a wide range of possible angles between the excavator and the truck being loaded;

- o % Cut Height: the excavations level corresponds to a certain percentage of the optimum height of cut of the selected excavator;

- o Material: the type of material to be processed using geotechnical or site information;

- o Mat Condition: refers to the expected difficulty in cutting the material, which ranges from "soft" to "very hard";

- o Key: refers to the site organisation (job efficiency) which can be from "poor" to "excellent" and Phi: refers to the material characteristics.;

- • Selection of an option which can be achieved by a project manager and based on the condition of the project. For example a project manager might select an expensive option at low risk by deploying certain resources that can work under severe weather conditions.

- • Record information in the database, establish dependences of activities and view information in MS-Project.

- • To reduce the development cost, minimise the learning process and reduce the implementation cost, the system was designed and implemented using MS Excel, MS Access, AutoCAD, MS Project and VBA.

TABLE 5: Shows the type of equipments used and site condition factor affecting the productivity of the activity

Type of Equipment (Bulldozer)	Bucket Capacity (Bc) – m3	Cycle time (Ct)- min	Vegetation (μ)				Clearing Depth (e)
			Very dense	Dense	Medium density	Weak density	
Ttta	3.9	0.33 + 0.035*D					0.125
Tttb	5.6	0.33 + 0.037*D					0.175
Tttc	11	0.33 + 0.035*D	0.70	0.60	0.55	0.50	0.200
Tttd	16.4	0.33 + 0.034*D					0.225
Working Condition/ Job efficiency (Ke)			Good	Average	Rather(below average)	Poor	
			0.83	0.75	0.67	0.58	

In RoadSim, certain 'subjective' variables are quantified through a judgemental decision based on professional experience on site. The project planners or construction managers will decide the selection of particular variables that really affect productivity of road activities.

5. CASE STUDY

RoadSim is a distinctive simulation model in comparison with previous developments of simulation models. It focuses on calculation of productivity and unit cost under different resource levels and site conditions for linear construction projects and in particularly in road construction. RoadSim is developed for master scheduling at pre-construction and bidding stages to analyse the total duration and cost of road construction activities. The RoadSim model provides an ideal solution for productivity and unit cost of road activities by selecting ideal equipment sets under different site conditions to maximise the productivity. A detailed case study is presented to validate the developed RoadSim simulation model as follows:

A case study is presented referring to the tests carried out using real life road construction projects. The case study uses a section of the A25, a road project constructed in Portugal between the year 2003 and 2005, see Figure 7. The section selected constituted Lot 2, between "Talhadas" and "Vouzela" and has a length of 17.085 km. The contractor established a new quarry in the area and installed a 200 ton asphalt plant.
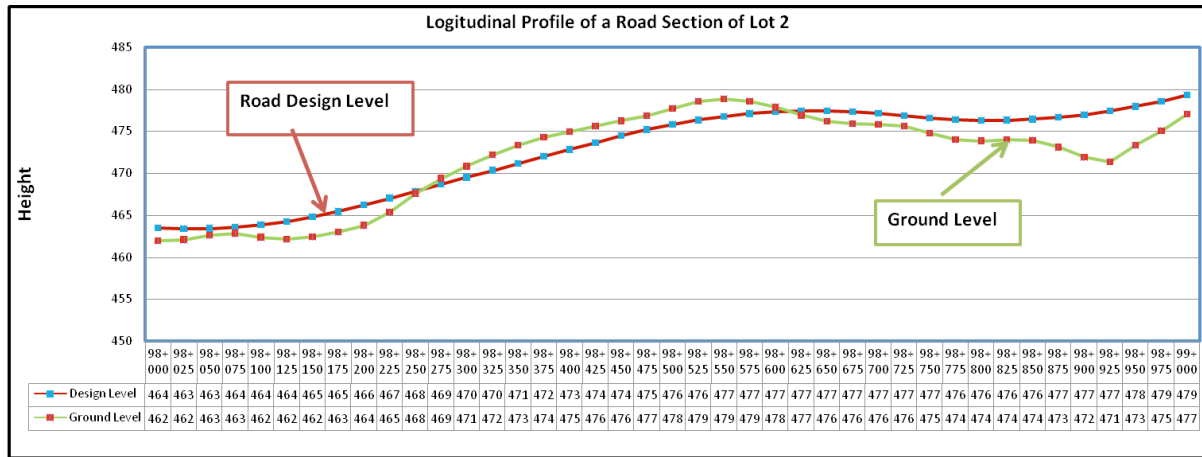
FIG 7. Profile of Lot 2 road project case study

The control of the project identified two management problems:

1. The economic results were slightly worse than planned;

2. There were risks about timely completion of the works.

A re-planning process was then undertaken. At that stage, RoadSim was introduced to test its capabilities and compare the respective performance and outputs with those corresponding to the control process.

After the construction activities and work quantities were introduced into the system, a simulation run was performed in order to obtain productivity of each activity and for every feasible construction alternative. However, since the works were already in progress and taking into account that the equipment mobilised for the works refers to a company strategy, the productivity outputs considered for comparison purposes are only those corresponding to the existing means at site; this included:

- Unit costs for every activity;

- Duration of execution for every activity;

- Scheduling of the works.

Before introducing the results of the models, it will be worthwhile to demonstrate the calculation of the RoadSim model, the following example shows how the productivity equation is used in calculating the duration needed for the activity of a road project such as 'clearing of vegetation', including grubbing and removal of trees, brush and roots with a diameter less than 1.0 meter.

The following equation has been used to calculate the duration of an activity:

$$P_h = (K_e * B_c * 60)/ (C_t * e * \mu)$$

Whereas,

P_h = Productivity of road activity per hour

K_e = Working condition/ Job efficiency factor

B_c = Bucket capacity of equipment used (Bulldozer) in m^3

C_t = Cycle time (time need to complete one cycle operation) in min

e = Clearing depth in meters

μ = Vegetation coefficient

From the BOQ, the estimated quantity of clearing activity in Lot 2 of the road project was 553,969.00 m3.

From Table 5, the following data are selected as per the site conditions by the project planner:

Type equipment used for this activity = Ttta (Bulldozer)

Working condition/ Job efficiency factor (K_e) = 0.75 for average condition

Assumed dozing of cleared material to a distance (D) = 40 m

Vegetation (μ) = 0.7 (very dense)

Clearing depth (e) = 0.125 m

Using the productivity equation show above,

Hourly Productivity (P_h) = (K_e * B_c * 60) / (C_t * e * μ)

  = (0.75*3.9*60)/ ((0.33+0.035*40)*0.7*0.125)

  = 1159.37 m^3/hr

Total duration required = Estimated quantity/productivity = 553,969.00/1159.37

  = 477.82 hrs.

The unit hour cost is calculated considering total cost of equipment which includes initial investment cost, operation and maintenance cost and salvage cost; divided by average economical working hour of the equipment. A detail calculation sheet of unit cost of equipment was developed and incorporated in the simulation model.

 Therefore, Unit cost of selected equipment for the bulldozer (Ttta) produced by "RoadSim" = £ 49.12 per hour

Total Cost of the selected equipment = £49.12 * 477.82

  = £23,470.52.

Cost per unit quantity of the activity = £ 23,470.52/ 553,969.00 = £ 0.04 per m^3

Similarly, all other road activity can be analysed and simulated in terms of productivity and unit cost of each activity under different site conditions.

TABLE 6: Example of Outputs of RoadSim for two activities in the case study

Activity	Option 1	Option 2	Option 3	Remarks
Fill from cut or borrow	87.5 m3/hr	120 m3/hr	232 m3/hr	More than 20 different results for each option can be generated under different site conditions. Results for each option are within 30% of the figures given in the table
Cut to spoil	90 m3/hr	185 m3/hr	215 m3/hr	More than 30 different results for each option can be generated under different site results. Results for each option are within 20% of the figures given in the table

Option 1: Equipment set - Excavator + tipper truck

Option 2: Equipment set - Bulldozer + Pay loader + tipper truck

Option 3: Equipment set – Bulldozer + Motor scraper

In the RoadSim system, the calculation of productivity and unit cost of road activity can be identified by selecting different types of equipment, working conditions and soil characteristics as per site conditions. Table 6 shows different results for 'cut to spoil' and 'fill from cut or borrow' activities of the case study using different conditions, equipment type and soil characteristics risk factors. As can be seen the results have a wide range of fluctuations suggesting that there is a high impact of the factors above on productivity. Calculations for all other activities in the Bill of Quantities are given in Table 7 using similar soil conditions, machineries and site conditions. The summary result of Lot 2 is presented in Table 7 and Table 8. The elements in Table 6 have been used to establish a preliminary schedule containing the construction durations. It is not the final schedule yet but a working element destined to define the work sequencing, verify compatibilities and rectify or confirm the envisaged construction methodology.

TABLE 7: Summary of simulation result provided by RoadSim in Lot 2 of case study

Item	Operation name	Work quantity	Estimated productivity (per hour)	Estimated duration (hrs)	Estimated cost (£)	No of available option
1	Clearing	553,969.00	1,113.45	497.52	27,698.45	1
2	Dozing	84,121.00	195.35	430.62	32,807.19	1
3	Fill from cut or borrow	929,533.00	232.44	3,999.10	1,859,066.00	3
4	Cut to spoil	1,174,696.00	215.85	5,442.19	1,867,766.60	3
5	Unstabilised gravel sub-base, base, shoulders and wearing course layers	46,602.00	63.50	733.89	144,466.20	3
6	Crushed stone sub grade without cement	2,760.00	63.50	43.46	44,629.20	2
7	Finishing off cut slopes	320,363.00	950.00	337.22	96,108.90	1
8	Finishing off fill slopes	225,064.00	156.25	1,440.41	87,774.96	1
9	Excavating for culverts	126,306.00	236.74	533.52	31,576.50	1
10	Backfilling for culverts	3,582.00	74.15	48.31	4,728.24	1
11	Laying pipe culverts	1,810.00	32.50	55.69	53,214.00	1
12	Laying pipe culverts	103.00	2.00	51.50	30,689.88	1
13	Laying pipe culverts	39.00	2.00	19.50	6,921.72	1
14	Laying pipe culverts	909.00	2.50	363.60	120,606.12	1
15	Excavating for trenches	1,085.00	3.00	361.66	24,238.90	2
16	Laying pipes for drainage	21,408.00	67.35	317.88	28,258.56	1
17	Laying pipes for drainage	31,540.00	6.00	5,256.66	208,794.80	1
18	Laying pipes for drainage	510.00	6.00	85.00	7,140.00	1
19	Permeable material for drainage	1,630.00	4.50	362.22	26,080.00	1
20	Backfilling for drainage	325.00	15.00	21.66	5,281.25	2
21	Excavating for open drains	21,083.00	16.00	1,317.68	65,989.79	2
22	Lining concrete for open drains	3,665.00	54.50	67.24	4,031.50	1
23	Precast concrete chutes	5,716.00	9.00	635.11	39,897.68	1
24	Precast concrete chutes	1,017.00	6.00	169.50	11,959.92	1
25	Crushed stone sub base & base without cement	125,282.00	42.52	2,946.08	2,025,809.90	2
26	Priming	470,242.00	995.00	472.61	162,942.28	1
27	Priming of asphalt layer	816,476.00	1,350.00	604.79	261,272.32	1

Option no 1: Equipment set - Excavator + tipper truck

Option no 2: Equipment set - Bulldozer + Pay loader + tipper truck

Option no 3: Equipment set – Bulldozer + Motor scraper

TABLE 8: Comparison of outputs in Lot 2

Activity	Unit	Quantity	Unit Cost (1000€)		Productivity Unit/hr		Total Construction Time (h)	
			Control (actual)	RoadSim	Control (actual)	RoadSim	Control (actual)	RoadSim
Bush clearing	m³	553 969	0.05	0.05	1113	1113	497	497
Top soil	m³	84 121	1.04	0.99	185	195	455	430
Cut to fill	m³	929 533	2.19	2.00	212	232	4385	3999
Cut to spoil	m³	1174696	1.29	1.59	175	216	6712	5442
Selected sub grade	m³	46 602	3.12	3.10	64	64	728	734
Stone base sub grade	m³	2 760	17.25	16.17	60	64	46	43
Scarification/recomp	m²	320 363	0.30	0.30	950	950	337	337
Trimming slopes fill	m²	126 306	0.45	0.25	87	156	1452	1440
Trimming slopes cut	m²	225 064	0.45	0.39	205	237	11098	950
Excav. Open drains	m³	3 665	1.15	1.10	52	54.5	70	67
Concrete open drains	m	5 716	6.86	6.98	9.5	9	601	635
Excav.subsoil drains	m³	21 408	1.34	1.32	66	67	324	318
Excav. Pipe culverts	m³	3 582	1.34	1.32	66	74	54	48
Pipes sub soil 200	m	31 540	6.65	6.62	6	6	5257	5257
Pipes sub-soil 300	m	510	14.05	14.0	6	6	85	85
Pipes sub soil 400	m	1630	16.87	16	4	4.5	408	362
Pipe culvert 1500	m	103	295.35	297.96	2	2	52	52
Pipe culvert 1200	m	39	176.0	177.48	2	2	20	20
Pipe culvert 1000	m	909	130.85	132.68	2.5	2.5	364	364
Pipe culvert 500	m	1 085	23	22.34	3	3	362	362
Half pipe chutes 500	m	1 017	12	11.76	6	6	169	169
Permeable material	m³	325	17.10	16.25	15	15	22	22
Backfilling subsoil drains	m³	21 083	3.10	3.13	15	16	1405	1318
Ditto pipe culverts	m³	1 810	3.10	2.94	15	32	121	56
Crushed material in sub base and base	m³	125 282	17.25	16.17	40	43	3132	2946
Dense bitumen macadam	ton	192 645	18	18	160	160	1204	1204
Bituminous concrete in intermediate layer	ton	10 880	29.50	29.47	140	140	78	78
Fine graded asphalt in wearing course	ton	48 051	32	31.75	130	130	370	370
Prime coat	m²	470 242	0.30	0.34	1005	995	468	473
Binder coat	m²	816 476	0.30	0.30	1200	1350	680	605

This preliminary schedule is based on the productivity of one single construction team. The number of teams is defined after a construction sequence is established. The number of teams may not be constant along the construction period since it depends on many variables going from "availability of space", "weather", and "compatibility with other works". It can be verified that in the cases where the cost of the materials is fixed, no deviation was noted between the real life project outputs and RoadSim. In the overall construction operation, the

difference in cost is only 0.3% (RoadSim's cost being lower). The main reason for the similar results is that similar road construction machineries have been used in the real project and in the simulation under the same soil characteristics and site conditions. However, if the factors influencing productivity has changes, the results of RoadSim can vary significantly as presented in Table 6.

The result achieved from the case study justifies the accuracy of the RoadSim model. For example, a comparison table of outputs between RoadSim model and actual site (control) is presented in Table 8 which was validated in a road project of Lot 2 in Portugal.

6. CONCLUSIONS

This paper discussed and presented a modular approach for modelling road construction operations. The modular approach uses the concept of an atomic model to break down construction activities from a high level into a very low level and to use this as modules for the modelling of the construction activities. Road construction activities, construction resources, working condition parameters and respective interactions have been identified and defined through a knowledge acquisition process based on 145 actual construction projects. This approach allowed the design of a system covering an entire and specific construction domain, hence providing specificity and simplicity. A computer based simulation model dubbed RoadSim was developed to encapsulate the rules and knowledge that were elicited from previous projects and technical information. The model is a decision support system which has the capabilities to develop road construction schedules.

Based on the information provided by the RoadSim simulation model regarding the time and cost of each construction activity, project planners will be able to assign the construction sequences of activities based on construction knowledge to develop the master schedule and determine initial construction cost of road projects. The output of the RoadSim model has been validated with a case study in road construction project. The model outputs and actual outputs of on-site have been compared and found to be close to the actual outputs received from the construction site and the model is useful at tendering and execution stages as a decision support system.

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