Dynamic planning of earthmoving projects using system dynamics

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Purpose The purpose of this paper is to present a dynamic planning model for earth moving operations through capturing the operations context level (scope change, skill level, etc.). **Method** Uncertainties, scope, and changes in project condition call for dynamic modeling of earthmoving operations. Static planning and scheduling methods such as CPM and PERT neglect – and are incapable of – considering project dynamics and causal-effect loops that exist between project variables. In an effort to address this challenge, system dynamic modeling and simulation is utilized in this research to plan and simulate earth moving operations. The developed model consists of three modules: (i) a work flow module that focuses on work execution from excavating the material until dumping it as demonstrated in; (ii) a resource module that captures the resources' interactions and estimates the required resources based on the variables governing the site condition and management requirement; and (iii) a cost module that estimates associated costs with project's operations. **Results & Discussion** The model was tested using a real case from Marzouk and Moselhi. The model outputs demonstrate that including the project context variables and their cause-effect loops to the planning stage of this category of projects improves the planning process. The developed system dynamic model is expected to enhance project modelling; capturing the interactivity among its variables to provide more realistic modelling for its schedule and cost. It also can assist members of project teams to predict a variety of likely scenarios and develop suitable action plans.

***Keywords**: earthmoving planning, system dynamics, simulation*

INTRODUCTION

Earthmoving operations are common in heavy construction projects. Considerable efforts have been made to develop efficient models and systems for estimating earthmoving operations' productivity and fleet configurations that yield optimum outcome[2,7,8,12,13]. Earthmoving operations exist in a dynamic environment with high influence from the operation's context on the performance. For instance, equipment breakdown, inclement weather, unexpected site conditions[9], scope change, and schedule pressure are factors that may give rise to uncertainty. Traditional scheduling methods such as CPM and PERT do not directly take into account such uncertainties[11].

Construction is inherently dynamic, involving multiple feedbacks[14]. Nevertheless, this dynamic nature has not been explicitly addressed by traditional planning methods such as CPM and PERT. Project failure can be attributed to poor representation of the inner and outer aspects of operations. Uncontrollable external forces are often cited but the real cause may be internal such as the results of the cause-effect relationships between the project variables. Good project management should take into account the adverse external influence as well as the internal structure of the project systems. It has long been recognized[10] that inadequate modeling of factors at the strategic level of projects results in their failure to achieve targeted objectives.

System dynamics approach can be used as a solution to capture the impact of such strategic factors on earthmoving operations. In construction, the use of system dynamics approach that considers approximately the entire construction operations as system consists of variables that interact overtime. This approach of modeling is practiced informally in the form of mental models. The mental models are nothing but models developed by mangers in their minds based on their accumulated experience to understand what are the causes and what are the expected effects. Usually such models are simple, developed for limited number of variables involved in cause-effect relationships. When the project gets larger with involvement of many variables, the human mind fails to comprehend and relate many variable interactions in a system. This difficulty prevails over by utilizing rules and regulations of system dynamics planning method as well as the computer computation.

The system dynamics approach of project management is based on a holistic view of the project management process that focuses mainly on the interactions of the system's variables in a feedback process. It offers a rigorous tool for describing, exploring, and analyzing of complex projects[15]. Variety of aspects influences project performance including development process, resources, project's scope, and targets[4]. These four aspects interact throughout the project cycle in a complex fashion to reach to the project goals. The traditional management methods describe the four mentioned aspects in a static fashion that account only for duration, cost, and resources. Bundling all the effective aspects of the project in single activity duration as the case in the network methods hinders better project planning and performance measurement. Furthermore, they tend to ignore project dynamics and cause-effect relationship that exists between the project's variables.

PROPOSED METHODOLOGY

The propose methodology utilizes system dynamics modeling technique to build special purpose model for earthmoving operations. The model accounts for the dynamic nature inherited in construction operations as well as for capturing the cause-effect relationships among the variables considered in the operations. The proposed model consists of three main modules. The first is work flow module that describes the work flow and its execution from the initial scope to completion. Cause-effect relationships arising from scope change, rework, and deviation of project from its planned duration and productivity are built. The second module is the resources module, which generates the required resources (e.g. excavators, loaders, labors, and trucks) based on the planned project duration, productivity, and scope of work. The third module is the cost module; designed to calculate direct and indirect costs of the operation being modeled. The cost module takes into account the dynamic nature of the operation and makes adjustments to generate as realistic cost as possible. The proposed system dynamics model is built in Vensim PLE ® Version 5. Due to space limitation, this paper focuses only on the development of work flow module as explained in the following section.

MODEL DESCRIPTION

A system dynamics simulation model is a series of differential equations based on feedback relationships that represent interactions among its elements[14]. The stocks, flows, and cause-effect relationships of the developed model are represented by equations designated with parentheses [e.g., (1)] and demonstrated in Appendix A. The work flow structure demonstrated in Figure 1 is adapted from Ford and Sterman[4]. Similar structures are also developed to represent project dynamics and its cause-effect feedback loops[1,3,5].

The first step in building the system dynamics model of earthmoving operation is to identify the model boundary. The model boundary identifies the model's scope by classifying the model's variables into endogenous (value changes during simulation run), exogenous (value remains constant during simulation run) and excluded variables. Table 1 summarizes the built model boundary.

Table 1. Model boundary

Endogenous	Exogenous	Excluded
Quality, actual productivity, actual duration, perceived productivity rate, schedule pressure, actual progress, forecasted productivity and required resources	Project deadline, scope change, equipment theoretical productivity, error rate.	Safety, fatigue, undiscovered error, secondary error cycle, resources constraints,

The developed system dynamics work flow structure is demonstrated in Figure 1. The stocks (represented by boxes) represent the work that either needs to be carried out or are already completed. The arrows represent the direction of work flow while the valves represent the rate at which work stocked is processed. The stock 'initial work to do' is the initial work scope; e.g. the material to be excavated and hauled to the dumping site (1). This stock is connected with the inflow 'added scope' (2) and the outflow 'reduction in scope' (3). The inflow accounts for the anticipated positive scope change during project execution phase while the outflow accounts for scope reductions. Such addition or reduction affects the project productivity. This effect is captured by using reference models that quantify the reduction rate of the productivity fleet due to scope change. The flow 'excavation' (4) represents the rate at which the excavators execute the work which is controlled by work scope and rate of excavation. Required rate of excavation (5) is determined by the planned excavation rate as well as available fleet keeping in mind the rate change is based on many factors such as equipment maintenance and schedule pressure. Excavated material is stocked in 'excavated material' sock (6). The loading rate (7) is determined by the stock 'excavated material' and available loading equipments.

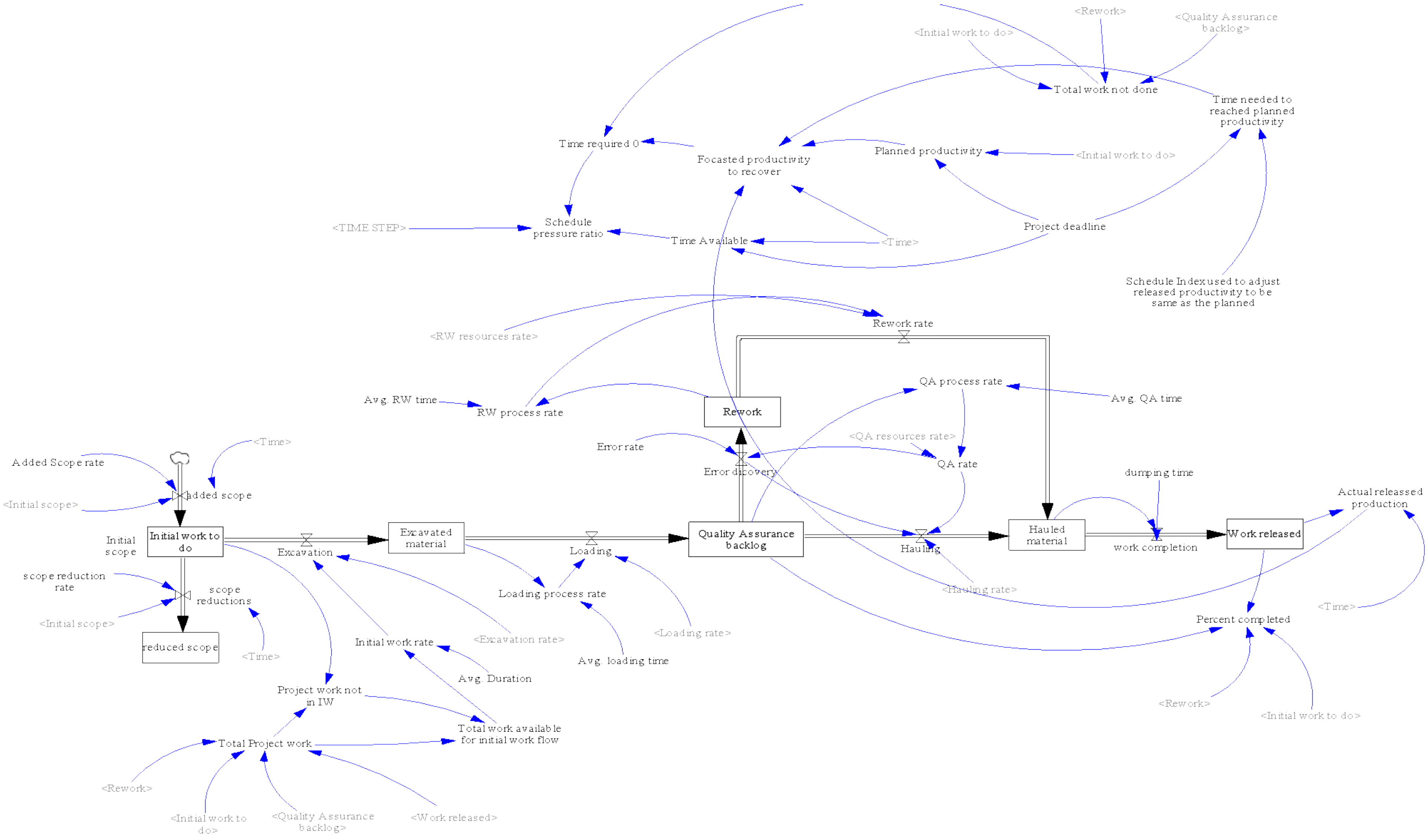

Fig. 1. System dynamics model of earthmoving flow of work operations

The stock 'quality assurance backlog' (8) is the point where the work is checked to meet set standards and specifications. The percentage of work that passes the quality check is ready to be hauled (9) while the work that does not pass the quality check is passed through a rework cycle (10, 11, and 12) It was assumed that the work will be reworked only one time to reach the required material quality; this means that the reworked quantities of work will pass quality standards. The reworked work after completion is admitted to material ready for hauling in stock 'hauled material' (13). The flow 'work completion' is the rate at which the hauled material is dumped at the construction site (14). Work released is the final actual productivity of the model and the actual productivity rate is calculated by dividing the quantity of 'work release' by the associated simulation time (15). This calculates the productivity rate at every time point during the execution phase. The described six stocks of the model are constrained by resources, change in scope, and schedule pressure.

MODEL TESTING

The model was tested using standards of system dynamics method[14]. The inputs parameters of the earthmoving operation are shown in Table 2. These are the inputs for the system dynamic model.

Table 2. Characteristics of the earthmoving operation

Item	Quantity
Project Scope	100,000
Planned duration	150 hours
Scope change	10% of initial scope
Excavators productivity	180 ton/hr in first 20 hrs then increase to 120 tone/hr
Loader productivity	200 ton/hr in first 20 hrs then increase to 216 tone/hr
Labor productivity	190+STEP(5,8)+STEP(10, 24) ton/hr
Quality and efficiency level.	80%

The model ran for 160 hrs; setting the STEP TIME equal to 0.125 hr (i.e., the time interval where the model updates its variables` states at the end of each interval). The model results show that the scope of work was completed in 155 hrs as shown in Figure 2. As it can be noticed from Figure 2, the total scope is the initial scope that was set at 100,000 ton and was subjected to scope change of +10% of the initial scope.

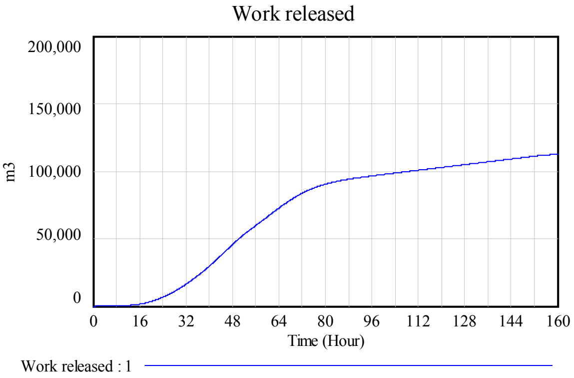

Fig. 2. Work accomplished

The model`s behavior is consistent with previous project models and demonstrates consistency with the common `S-curve`. As the work progresses, the initial work decreases slowly causing the quality assurance, rework, and hauled material stocks to build up gradually. The model behavior shown in Figures 3, 4, and 5 is close to previously developed models in construction such as those of Cooper[3], Ford and Sterman[4], and Lyneis et al.[6]. The peak shown in Figures 3, 4 and 5 represents the accumulation of stock due to accumulation of error that generates more work or due to the unbalance between productivity of various stocks. Clearly this is due to the developed cause-effect relationships. The total project cost is shown in Figure 6.

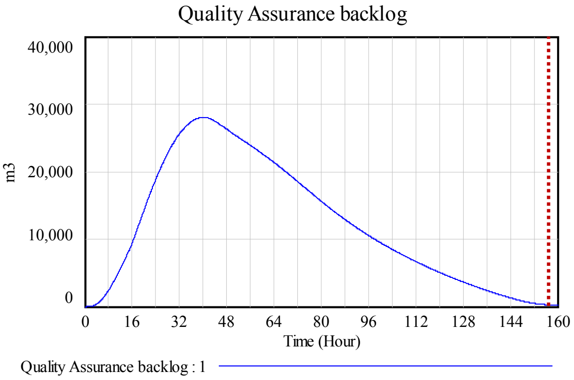

Fig. 3. Work waiting for quality check

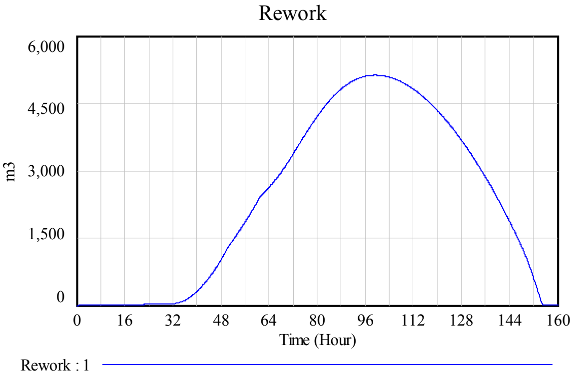

Fig. 4. Work needs to be reworked

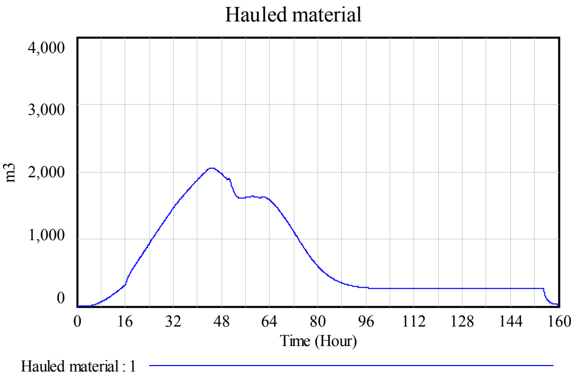

Fig. 5. Hauling stock

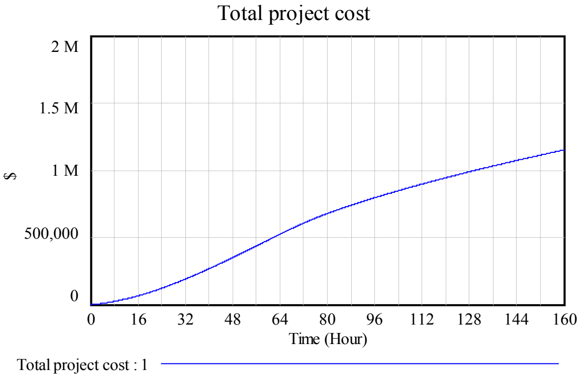

Fig. 6. Total actual cost of the operation

The project planed duration was set to be 150 hrs. After running the model, the scope of work was completed in 155 hours. The ratio of schedule pressure (time required to complete the work divided by available time) is calculated at every hour during running the simulation model as shown in Figure 7. The figure shows high schedule pressure ratio at the start of work (first 16 hrs). This is compatible with what is seen in construction execution where productivity increases gradually as the operations progress. The rest of the model shows steady schedule pressure ratio ranging from 0.05-0.3

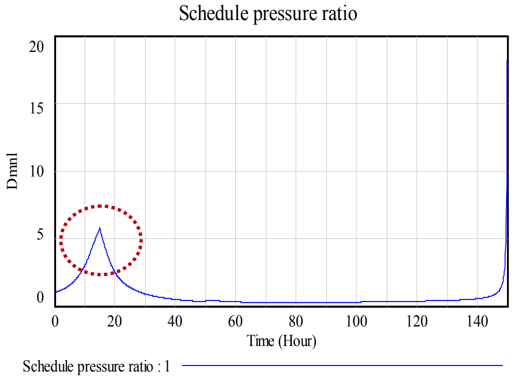

Fig. 7. Total actual cost of the operation

Figure 7 shows the buildup of the schedule pressure in the case simulated in this paper. This allows for finding the bottle-necks resulting from simulated high schedule pressure and subsequently taking corrective actions in the form of increasing the resources to prevent schedule slippage.

CONCLUSION

This paper presented a dynamic planning model for earthmoving operations by utilizing system dynamics. The proposed model can capture the cause-effect relationships that exist among the variables impacting earthmoving operations. The developed model allows for capturing the neglected dynamics in tradition planning methods and overcoming their static nature. The proposed model can predict the required resources, productivity, schedule slippage, and time needed to recover. Furthermore, it accounts for scope change during execution of the project and for smoothening of assigned resources to perform the new increased or decreased scope. This model can be enhanced by adding the effect of other variables such as weather, overtime, skill level and equipment maintenance.

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APPENDIX A

MODEL’S EQUATIONS

1-Initial work to do= INTEG (added scope-Excavation-scope reductions, Initial scope).
Units: m3
2- Added scope= IF THEN ELSE (Time= 50, Initial scope*Added Scope rate, 0).
Units: m3/Hour
3-Scope reductions= IF THEN ELSE (Time=150, Initial scope*scope reduction rate, 0).
Units: m3/Hour
4-Excavated material= INTEG (Excavation-Loading, 0) Units: m3/Hour
5-Excavation rate= Excavator productivity*"No. of excavators" Units: m3/Hour
6- Excavation= MIN (Excavation rate, Initial work rate) Units: m3/Hour
7-Loading=MIN (Loading process rate, Loading rate) Units: m3/Hour
8-Quality Assurance backlog= INTEG (Loading-Error discovery-Hauling, 0).
Units: m3
9-Hauling = MIN (QA rate-Error discovery, Hauling rate)
Units: m3/Hour
10-Error discovery=Error rate*QA rate.
Units: m3/Hour
11-Rework= INTEG (Error discovery-Rework rate, 0) Units: m3
12-Rework rate= MIN (RW resources rate, RW process rate).
Units: m3/Hour
13- Hauled material= INTEG (Hauling + Rework rate-work completion, 0).
Units: m3
14- Work completion= Hauled material/dumping time.
Units: m3/Hour
15-Work released= INTEG (work completion, 0) Units: m3