DYNAMIC RESOURCE MODELING AND GRAPH THEORY

Pooyan Aslani[1] and Symeon Christodoulou[2]

ABSTRACT

Construction schedules are very sensitive to resource availability, since both time and cost are dependent on resource assignments. Furthermore, since resource-constrained schedules contain resource dependencies between activities, dynamic network solution methodologies and resource-constrained scheduling should be applied whenever there are limited resources available for a project and the competition for these resources among the project activities is keen. Resource-constrained scheduling is particularly important in managing multiple projects with fixed resources of staff or equipment, especially when the workload for these resources is heavy. The paper presents one such simulation-based, resource-constrained scheduling methodology. Simulation is used (by means of commercially available event-driven simulation software) to schedule construction projects under resource constraints and optimize the resource-constrained dynamic flow network solution. In the end, a comparison between traditional CPM-based scheduling software and the resource-constrained schedule is presented, pointing out that it is better to consider resource-constrained scheduling and perform scehdule analysis at the resource level and not the activity level (something not feasible in traditional CPM analysis).

KEY WORDS

Resource-constrained scheduling, graph theory, simulation.

INTRODUCTION

Like a tree, a network (or graph) is a set of nodes connected by a set of edges or links. The links in a network may each have an associated direction, in which case the network is called directed network. Each link may also have associated cost which, in the case of a network representing a construction schedule, might be the time it takes to finish an activity. A critical path is one of the longest sequences of tasks that must occur to finish the project, and items that lie along the critical path are important because a slip in any of their schedules will change the completion time of the entire project.

Any project can be subdivided into a list of activities or tasks (a more precise terminology of the critical path method for planning and scheduling, actually, refers to tasks as scopes of work that are components of activities). The level of detail of specific activities may vary, but it is customary of all critical path methods of scheduling that each activity can

[1] PhD Candidate, Civil Engrg. Department, Center for Construction Management Technology, 6 Metrotech Center, Polytechnic Univ., Brooklyn, NY 11201, Phone +1 718/260-3864, pooyanpoly@gmail.com
[2] Assistant Professor, Civil and Envir. Engrg. Department, 75 Kallipoleos Street, P.O.Box 20537, Univ. of Cyprus, 1678 Nicosia, Cyprus, Phone +357 22892270, FAX +357 22892295, schristo@ucy.ac.cy

start only upon a 100 percent completion of some other activity, except for a first or starting activity that does not have a stated predecessor (relationships between activities are usually of “finish-to-start” type). Furthermore, the durations used to define the network activities are functions of the resources required to complete each activity, rather than a function of the availability of such resources.

Much of the above discussion has focused on static models, that is, problems that have no underlying temporal dimensions. Static network models provide good mathematical representations of great many applications. In some other applications, however, such as scheduling of people and equipment, time is an essential ingredient. In such cases one needs to use dynamic network flow models to account properly for the evolution of the underlying system over time.

Dynamic network models arise in many problems including resource-constrained schedules. Resource-constrained schedules contain resource dependencies between activities that should be applied whenever the resources available for a project are limited and the competition for these resources among the project activities is keen. In effect, delays are likely to occur in such cases as activities must wait until common resources become available. To the extent that resources are limited and the demand for the resource is high, this waiting may be considerable. In turn, the congestion associated with these waits represents increased costs, poor productivity and, in the end, project delays. Schedules made without consideration for such difficulties can be completely unrealistic.

Resource-constrained scheduling is particularly important in managing multiple projects with fixed resources of staff or equipment, especially when the workload for these resources is heavy. In the “maximum flow problem”, one maximizes the number of flow units (resources) that can pass through the network from node s to node t per unit of time while satisfying the arc capacities. In other words, the maximum flow problem determines the maximum steady state flow per unit of time between two nodes, so we might refer to this problem as the static flow problem. On the other hand, the “maximum dynamic flow problem” maximizes the total flow (flow that we can send between two nodes within a given period). The maximum flow problem is a fundamental problem in graph theory, and the dynamic version of the maximum flow problem allows the graph underlying the flow network to change over time. The graph receives, in real time, corrections to its structure or capacities and consequently the value of the maximum flow is modified. Graph theory also allows the study and solution of “minimum cost flow” problems in capacitated (time-dependent) dynamic networks, in which flows from source nodes should be sent, in minimum total cost, to end nodes such that the flows on used links do not exceed their capacities.

While algorithms for optimal solution of the resource-constrained problem exist, they are generally too computationally expensive to be practical for all but small networks. To compliment the capabilities of graph theory in resource-constrained scheduling and capture the interrelationships and flows of events and resources one needs to also consider adding simulation to such scheduling paradigms.

The paper presents one such simulation-based, resource-constrained scheduling methodology. Simulation is used, by means of commercially available event-driven simulation software (*Simul8* by Visual Thinking International), to schedule construction projects under resource constraints. Simulation as a scheduling and planning technique is briefly discussed and the simulation model under *Simul8* is presented. In the end, a comparison between traditional CPM-based scheduling software (*Primavera Project Planner* by Primavera Systems) and the resource-constrained schedule (*Simul8*) is presented.

RESOURCE-CONSTRAINED SCHEDULING

Resource-constrained scheduling represents a considerable challenge and source of frustration to researchers in mathematics and operations research. While algorithms for optimal solution of the resource-constrained problem exist, they are generally too computationally expensive to be practical for all but small networks (of less than about 100 nodes) (Patterson 1984). The difficulty in the resource-constrained project scheduling problem arises from the combinatorial explosion of different resource assignments which can be made and the fact that the decision variables are integer values representing all-or-nothing assignments of a particular resource to a particular activity. In contrast, simple critical path scheduling deals with continuous time variables. Construction projects typically involve many activities, so optimal solution techniques for resource allocation are not practical.

One possible simplification of the resource-oriented scheduling problem is to ignore precedence relationships. In some applications, it may be impossible or unnecessary to consider precedence constraints among activities. In these cases, the focus of scheduling is usually on efficient utilization of project resources. To ensure minimum cost and delay, a project manager attempts to minimize the amount of time that resources are unused and to minimize the waiting time for scarce resources. This resource-oriented scheduling is often formalized as a problem of "job shop" scheduling in which numerous tasks are to be scheduled for completion and a variety of discrete resources needs to perform operations to complete the tasks. Reflecting the original orientation towards manufacturing applications, tasks are usually referred to as "jobs" and resources to be scheduled are designated "machines." In the provision of constructed facilities, an analogy would be an architectural/engineering design office in which numerous designs related tasks are to be accomplished by individual professionals in different departments. The scheduling problem is to ensure efficient use of the individual professionals (i.e. the resources) and to complete specific tasks in a timely manner (Hendrickson 1984).

The simplest form of resource-oriented scheduling is a reservation system for particular resources. In this case, competing activities or users of a resource pre-arrange use of the resource for a particular time period. Since the resource assignment is known in advance, other users of the resource can schedule their activities more effectively. The result is less waiting or "queuing" for a resource. It is also possible to inaugurate a preference system within the reservation process so that high-priority activities can be accommodated directly.

In the more general case of multiple resources and specialized tasks, practical resource-constrained scheduling procedures rely on heuristic procedures to develop good but not necessarily optimal schedules. While this is the occasion for considerable anguish among researchers, the heuristic methods will typically give fairly good results. An example heuristic method is provided in the next section. Manual methods in which a human scheduler revises a critical path schedule in light of resource constraints can also work relatively well. Given that much of the data and the network representation used in forming a project schedule are uncertain, the results of applying heuristic procedures may be quite adequate in practice (Ahuja 1984).

Numerous heuristic methods have been suggested for resource-constrained scheduling. Many begin from critical path schedules which are modified in light of the resource constraints. Others begin in the opposite fashion by introducing resource constraints and then imposing precedence constraints on the activities. Still others begin with a ranking or classification of activities into priority groups for special attention in scheduling. (Patterson et al. 1984) One type of heuristic may be better than another for different types of problems. Certainly, projects in which only an occasional resource constraint exists might be best scheduled starting from a critical path schedule. At the other extreme, projects with numerous important resource constraints might be best scheduled by considering critical resources first (Ammar and Mohieldin 2002).

Two problems arise in developing a resource-constrained project schedule. First, it is not necessarily the case that a critical path schedule is feasible. Because one or more resources might be needed by numerous activities, it can easily be the case that the shortest project duration identified by the critical path scheduling calculation is impossible. The difficulty arises because critical path scheduling assumes that no resource availability problems or bottlenecks will arise. Finding a feasible or possible schedule is the first problem in resource constrained scheduling. Of course, there may be a numerous possible schedules which conform to time and resource constraints. As a second problem, it is also desirable to determine schedules which have low costs or, ideally, the lowest cost.

In many networks, links have *capacities* in addition to costs. Each link can carry *flow* that is not greater than its capacity. A network with capacities on its links is called a *capacitated network*. Given a capacitated network, the maximum flow problem is to determine the largest flow possible through the network from a specific source node to a specific sink node. In this paper we have tried to maximize flow of resources and minimize cost flow.

A resource-constrained scheduling problem is defined as a project consisting of a set of interrelated activities which can be interrupted or overlapped, and of resources which are limited in quantity and availability. Under these assumptions, a dynamic model could find the optimal time-cost combination. The characteristics of resource-constrained project scheduling are activities and resources.

DYNAMIC SCHEDULING SIMULATION

Simulation as a planning and scheduling technique has been used in construction management since the 1970s. The majority of simulation applications were directed at the analysis of construction processes. Few applications of simulation were directed at scheduling construction projects at the project level, and none of them can handle a resource-constrained problem. Although simulation has been accepted in academia, it has not been adopted on a large scale in the construction industry, primarily due to the inherent difficulty in its use and the lack of suitable user-friendly commercial application tools that can be utilized by construction professionals. One should note, though, that significant steps have been taken in that direction with such software tools as MicroCYCLONE (Halpin, D. and Riggs, L. S., 1992), STROBOSCOPE (Martinez, J.C., 1996) and Simphony (AbuRizk, S. and Mohamed, Y., 2000). As the authors of these software tools state, "*MicroCYCLONE is a* *microcomputer-based simulation program designed specially for modeling and analyzing site level processes which are cyclic in nature. In broader terms, it can be used to model construction operations which involves the interaction of tasks with their related duration, and the resource unit flow routes through the work tasks are the basic rationale for the modeling of construction operations*". "*STROBOSCOPE is a simulation programming language based on the activity scanning simulation paradigm and activity cycle diagrams. Although designed specifically for the modeling of construction operations, STROBOSCOPE can be used to model operations in any domain". "Simphony is an integrated environment for building special purpose simulation tools for modeling construction systems".*

Unlike other planning and scheduling techniques, simulation is a dynamic comprehensive technique that provides a true representation of the output behavior as it evolves over time. Simulation can determine output based on variations in input (Halpin and Riggs 1992) and thus incorporate the uncertainty and complex interrelationships of resources that govern construction schedules. This paper presents an application of general-use simulation tools to resource-scheduling problems.

SCHEDULING SIMULATION USING *SIMUL8*

An event-driven simulation software called "*Simul8*" has been used to demonstrate the interactions in resource-constrained construction scheduling processes. It intenerates CPM capabilities with those of simulation. In integrating Simul8, different characteristics of a construction project were considered. These included the dependencies among activities, stochastic activity durations, activity prioritization, activity interruption, activity cost, resource availability, resource sharing, resource travel time and resource shift pattern. Although Simul8 has been developed to model manufacturing operations, it can be seen that it can also be used for construction processes as well.

Simul8 uses activity-on-node networks to model construction processes, with each activity in the network having the following properties:

- Name (activity identity and description)
- Duration (time to process the activity, which can be set via a distribution)
- Resources (resource requirements to perform task)
- Efficiency (specified productivity of resources)
- Routing in (how work flow enters the activity)
- Routing out (disciplines by which the work flow leaves the activity)
- Label action (specifies work flow label value)
- Priority (how this activity competes against others for resources)
- Graphic (defines the activities appearance and animation)

Resources are items in the model that activities can be set to require before each activity can be processed. Thus, they represent laborers or equipment. Activities cannot begin working until both work flow and the specified resource requirements are available. Resources can also be "shared" between multiple activities, favoring activities with highest priority settings. The properties of resources are as follows:

- Name
- Number available

- Pool resource (“pool” one or more resource available)
- Travel (travel time for resource movements between objects)
- Graphic (change the object’s appearance and visual behavior)

MODEL IMPLEMENTATION

In the present research, *Simul8* is used to schedule a highway construction project. The case study is based on a sample project in Primavera® P3 e/c for Construction. The project activities are given in Table 1 and the associated resource requirements are shown in Table 2. The CPM analysis of the unconstrained project (i.e. the case of not assigning resources) results in a project duration of 147 workdays. The project was then leveled (resource-constrained schedule) with the condition that the “Loader Backhoe 80 HP” daily assignment should not exceed two units, resulting in a project duration of 152 workdays.

Table 1: Sample Project (activity/logic listing)

Activity ID	Activity Name	Original Duration	Predecessors
1	GENERAL CONDITIONS	0	
2	EXCAVATE RETAINING WALL	12	
3	CONSTRUCT CONCRETE BARRIER AGAINST WALL	6	
4	REMOVE GUIDE RAIL	4	2
5	EXCAVATE FOR ELECTRICAL	10	4
6	INSTALL TEMP. ELECTRICS	15	4
7	PLACE TEMP. CONST. BARRIER	6	4
8	REMOVE TEMP. PAVEMENT	9	7
9	REMOVE TEMP. CONST. BARRIER	5	7
10	INSTALL ELECTRIC CONDUITS & STRUCTURES	19	5, 6, 8
11	REGRADE AREA	7	8
12	INSTALL POWER & LIGHTING	15	10
13	SUBGRADE PREPARATION	14	12
14	PLACE AGGREGATE & ASPHALT BASE COURSE	20	4, 13
15	PLACE ASPHALT STABILIZED COURSE	27	14
16	PLACE 2 SURFACE COURSE	10	15
17	STRIPE ROADWAY	9	16
18	REMOVE TEMP. BARRIER	4	17
19	PROJECT COMPLETE	0	1, 3, 18

The resource-constrained problem was then modeled in *Simul8* (Figure 1). Activities are shown as nodes and arrows indicate the relationships among activities. As the simulation progress, workflows start traveling among activities and as soon as they reach an activity that activity requests the assigned resources (they have been shown on the bottom of Figure 1). Upon completion of the activity the released work items will travel to the next activity in the network.

Table 2: Sample Project (daily resource requirements)

Activity ID	Resource Assignments
4	Foreman[0.25],Loader/Backhoe 80 H.P.[1],Highway Labor [1],Equipment Operator [1]
5	Foreman[0.25],General Laborer[1],Loader/Backhoe 80 H.P.[1],Equipment Operator - Light[1]
6	Electrician[3],Foreman[0.25]
7	Foreman[0.25],General Laborer[1],Truck Crane[1],Equipment Operator[1]
8	Foreman[0.25],General Laborer[2],Loader/Backhoe 80 H.P.[1],Equipment Operator[1]
9	General Laborer[1],Foreman[0.25],Equipment Operator[1],Truck Crane[1]
10	Electrician[3],Foreman[0.25],Skilled Laborer[2],Truck Crane[1]
11	Foreman[0.25],Dozer 200 H.P.[1],Equipment Operator[1]
12	Electrician[3],Skilled Laborer[2],Foreman[0.25]
13	Foreman[0.25],Roller Steel Wheel[0],Equipment Operator[1],Loader/Backhoe 80 H.P.[1]
14	Foreman[0.25],Equipment Operator[3],Aggregate Spreader[0],Roller Tandem[0],Dozer 200 H.P.[0],Loader/Backhoe 80 H.P.[1]
15	Foreman[0.25],Asphalt Paver 130 H.P.[1],Roller Steel Wheel[0],Equipment Operator[1],Loader/Backhoe 80 H.P.[1]
16	Foreman[0.25],Asphalt Paver 130 H.P.[1],Equipment Operator[1],Roller Steel Wheel[0],Loader/Backhoe 80 H.P.[1]
17	Foreman[0.25],Paint Stripper S.P.[1],Truck - Flatbed 3 Ton[1],Truck Driver - Heavy[1],Equipment Operator[1],Loader/Backhoe 80 H.P.[1]
18	Truck Crane[1],Equipment Operator[1],Foreman[0.25],General Laborer[1]

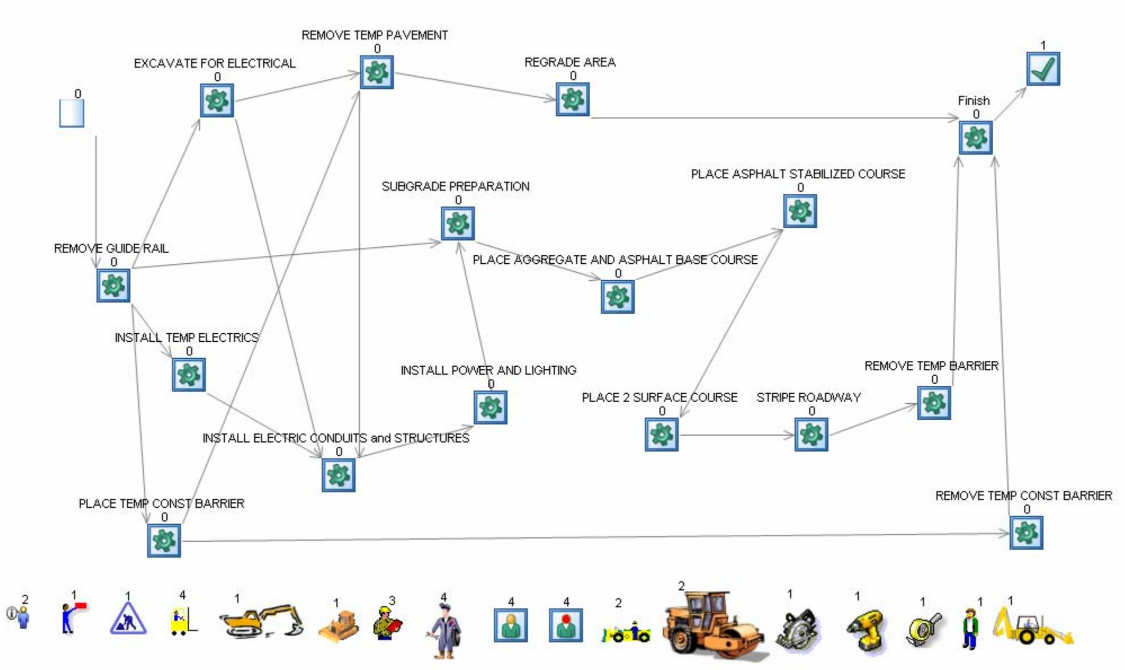

Figure 1: *Simul8* Model

MODEL COMPARISON

The resource-constrained dynamic flow network solution obtained from *Simul8* is 146 workdays (as compared to 152 workdays from the traditional CPM-based software). The results (shown in Tables 3 and 4) are primarily due to the increased optimization obtained in dynamic-flow simulations as opposed to static CPM techniques. CPM-based static network project solutions calculate schedules based on the resource requirements of each task and not the availability and interaction of resources assigned to these tasks.

Table 3: Comparison of Results for the Resource-Constrained Schedule Finish Dates

Activity		**Resource-Constrained (leveled) CPM dates**		**Resource-Constrained (leveled) CPM dates**				**Simulation Results[4]**	
ID	Duration	Start Date	Finish Date	Start Date	Finish Date	Start Date	Finish Date	Start Date	Finish Date
		(calendar dates[1])		(ordinal dates[2])		(in workdays[3])		(in workdays[3])	
1	0		04-Oct-04						
2	12	04-Oct-04	19-Oct-04	-	15	0	11		
3	6	04-Oct-04	11-Oct-04	-	7	0	5		
4	4	20-Oct-04	25-Oct-04	16	21	12	15		5
5	10	26-Oct-04	08-Nov-04	22	35	16	25		15
6	15	26-Oct-04	15-Nov-04	22	42	16	30		15
7	6	26-Oct-04	02-Nov-04	22	29	16	21		9
8	9	09-Nov-04	19-Nov-04	36	46	26	34		27
9	5	03-Nov-04	09-Nov-04	30	36	22	26		15
10	19	22-Nov-04	16-Dec-04	49	73	35	53		46
11	7	22-Nov-04	30-Nov-04	49	57	35	41		34
12	15	17-Dec-04	06-Jan-05	74	94	54	68		60
13	14	07-Jan-05	26-Jan-05	95	114	69	82		74
14	20	27-Jan-05	23-Feb-05	115	142	83	102		95
15	27	24-Feb-05	01-Apr-05	143	179	103	129		123
16	10	04-Apr-05	15-Apr-05	182	193	130	139		131
17	9	18-Apr-05	28-Apr-05	196	206	140	148		141
18	4	29-Apr-05	04-May-05	207	212	149	152		146
19	0	04-May-05	04-May-05	212	212	152	152		146

[1] The calendar dates are calculated based on an assumed project start date of 04-Oct-04.

[2] The ordinal dates are calculated by counting the number of days from the start of the project (day 0), including weekends/holidays.

[3] The ordinal dates are calculated assuming no weekend/holidays exist in between, as if there is an uninterrupted workflow.

[4] The results are obtained by simulating the resource-constrained network (maximum dynamic flow problem) in *Simul8*.

The summarized results are shown in Table 4. The case study project (with an assumed start date of 04-Oct-04) has an unconstrained completion date of 28-Apr-05 for a total duration of 206 calendar days (equal to 206*5/7 = 147 workdays). The resource-constrained schedule solved by traditional CPM techniques results in an expected completion date of 04-May-05 (212 calendar days, i.e. 212*5/7 = 152 workdays).

Table 4. Summary of Resukts

Computed Project Dates	CPM Calculations (unconstrained schedule)	CPM Calculations (resource-constrained schedule)	Simulation Results (maximum dynamic flow problem)
Early Start	4-Oct-04	4-Oct-04	
Early Finish	28-Apr-05	4-May-05	
Duration (calendar days)	206.00	212.00	
Duration (work Days)	147.14	151.43	145.6

Still another comparison, and indication of the achieved optimization level, is the resource usage for all possible paths in the network (a subset of the obtained results is shown in Table 5).

Table 5: Sample Report on Activity and Resource Usage

Activity/Resource	Metric	Value
Subgrade Preparation	Waiting %	97.32874
Subgrade Preparation	Working %	2.67126
Subgrade Preparation	Blocked %	0
Subgrade Preparation	Stopped %	0
Subgrade Preparation	Number Completed Jobs	1
Subgrade Preparation	Minimum use	0
Subgrade Preparation	Average use	0.13
Subgrade Preparation	Maximum use	1
Subgrade Preparation	Current Contents	0
Subgrade Preparation	Change Over %	0
Subgrade Preparation	Off Shift %	0
Truck Crane	Utilization %	8.98885
Truck Crane	Minimum Use	0
Truck Crane	Current Use	0
Truck Crane	Average Use	0.08989
Truck Crane	Maximum Use	1
Truck Crane	Traveling %	0
Truck driver heavy	Utilization %	0.71496
Truck driver heavy	Minimum Use	0
Truck driver heavy	Current Use	0
Truck driver heavy	Average Use	0.02145
Truck driver heavy	Maximum Use	1
Truck driver heavy	Traveling %	0

The simulation of the maximum dynamic flow problem can output several metrics that help identify the criticality of each path of activities and the one that is the most critical in terms of resource usage, regardless of which path is critical in terms of time (traditional CPM calculation). Among the metrics reported for each activity and resource are: waiting percent, working percent, blocked percent, stopped percent, number of completed jobs, and minimum, average and maximum use. These metrics should be helpful in schedule analyses such as resource optimization, or claims on work progress, delays and understaffing of projects.

CONCLUSION

An application of simulation techniques to the resource-constrained scheduling problem has been presented. The aforementioned simulation-based solution of the sample project network seems to provide more detailed and optimized results than traditional CPM-based methodologies, primarily due to the increased efficiency in terms of resource allocation and interaction provided by the simulation method. Since the described simulation approach does not require any data other than commonly used project data (activities, dependencies, durations and activity resources) and yet arrives at more optimized results compared to CPM, it is better to consider resource-constrained scheduling and perform the analysis at the resource level and not the activity level (something not feasible in traditional CPM analysis).

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