Proceedings of the 2008 Winter Simulation Conference
S. J. Mason, R. R. Hill, L. Mönch, O. Rose, T. Jefferson, J. W. Fowler eds.

SIMULATION-BASED, OPTIMIZED SCHEDULING OF LIMITED BAR-BENDERS OVER MULTIPLE BUILDING SITES

Hoi-Ching Lam
Ming Lu

Dept. of Civil and Structural Engineering
Hong Kong Polytechnic University
Hong Kong, CHINA

ABSTRACT

In the construction industry, a specialist subcontractor manages a taskforce of single-skilled laborers to work on multiple construction sites, aiming to minimize the total cost and stay profitable and competitive. This paper presents a simulation-based approach to assist the subcontractor in scheduling the application of limited laborer resources to handle jobs over multiple concurring sites. Factoring in technological constraints, repetitive building cycles, alternative method options, and the limited quantity of skilled laborers, we resort to computer power (including simulation and optimization algorithms resulting from recent research) in search of the best combination of construction methods at individual sites along with the optimum size of labor force, aimed to find the least cost for completing the jobs at all sites. A case study of bar-bender scheduling over three sites by use of an in-house computer tool results in the optimum method combinations, the optimum crew size, and the optimum resource schedule.

1 INTRODUCTION

In order to improve resource utilization rates and minimize the total project cost, it is common practice that a general contractor relies on subletting specialty construction tasks to specialist subcontractors. In each construction site, different subcontractors are responsible for carrying out their own craft. The present research looks into the skilled laborer resource allocation planning practice by specialist subcontractors in the construction industry. In Hong Kong, training and employment of single-skilled laborers remain the industry norm. In this situation, a specialist subcontractor has to manage a single-skilled labor force to work on multiple, concurring construction sites, with the aim of staying profitable and competitive. The ideal situation is to retain a stable labor crew and to make full use of labor resources available to carry out the tasks on multiple jobsites. For example, the common practice is for a bar bending subcontractor to take multiple jobs at different building sites over the same time period in Hong Kong. The current construction management practice, however, lacks a scientific solution to guide the cost-effective scheduling of those critical skilled labor resources. In July and August of 2007, Hong Kong bar benders put on strike to fight for under-employment, higher pay and shorter work hours. The bar benders' grievance partly could be attributed to lack of management efficiency in scheduling "bar bender" resources in a multi-site, multi-project context, resulting in bar-benders' high idling rate and lack of job security. This has motivated us to develop an effective decision support means for tackling the mind-boggling puzzle of scheduling limited skilled labor force to handle jobs at multiple sites. It is worth mentioning that in the real world, it is unrealistic to implement a "rotation door" policy in managing skilled laborers, which means hiring people only when they are needed and removing them from payroll on those days when they have no or inadequate work to do. As such, one concern in construction project planning is to level out the labor resource requirement profile over the project period.

In this paper, we resort to a case study of allocating bar-bender resources to three concurring sites to elucidate on the problem of skilled laborer scheduling in a multi-project context. Factoring in technological constraints, repetitive building cycles, alternative method options, and the limited quantity of skilled laborers, we take advantage of computer power (including simulation and optimization algorithms resulting from recent research) in search of the best combination of construction methods at individual sites along with the optimum size of labor force that would lead to the least cost for completing the jobs at all sites. The resulting substantial reduction in the total duration or cost comes solely from improvements in the efficient use of time and resources. That would deliver cost savings to the subcontractor while justifying pay raise for the laborers. Before we formulate the problem, related literature on resource-constrained scheduling is briefly reviewed first.

978-1-4244-2708-6/08/$25.00 ©2008 IEEE

2 LITERATURE REVIEW

For construction project planning, critical path method (CPM) is the most popular analytical technique. CPM-based scheduling has become a standard project management methodology in both university curriculums and industry practices. Nevertheless, CPM has limitations when applied to repetitive project scheduling (Reda 1990; Hegazy and Wassef 2001). As CPM networks for projects with repeating units of work have a ladder-like appearance, the number of these precedence links and nodes will likely be large and the network may appear unnecessarily complicated (Harris and Ioannou 1998). CPM is ineffective and cumbersome for scheduling linear continuous projects but extremely effective for more complex and discrete type projects (Yamin and Harmelink 2001).

Generally speaking, applying CPM in the context of planning construction projects entails the representation of largely non-repetitive, finish-to-start logic between construction activities as imposed by construction technology, aiming to maximize the utilization of limited resources and minimize the total project duration under resource-availability constraints. In contrast with repetitive scheduling techniques, achieving resource work continuity is usually not taken as the primary scheduling constraint while interrupting the activity progress (resulting in prolonged activity duration) is allowed to alleviate temporary resource shortages as long as the overall scheduling objective at the project level is attainable (e.g. shorter total project duration.)

Given its clarity, flexibility, and ease to manipulate, CPM still holds the potential for resolving practical resource allocation problems. Recent worldwide surveys found that the majority of schools, project owners and construction professionals indicated their preference of applying CPM scheduling (Liberatore et al. 2001; Galloway 2006a and 2006b). Current resource-loaded CPM provides the flexibility to model the resource constraints in a construction project definition. The *Primavera Project Planner* (*P3*) has become a standard methodology for construction project management in both university curriculums and industry practices (Liberatore et al. 2001; Galloway 2006a and 2006b).

Compared with conventional mathematical programming techniques and heuristic methods, evolutionary algorithms lend themselves better to optimizing the complicated project scheduling problems with resources constraints. Genetic algorithm (GA), which was conceptualized by John Holland in the 1970s, is the most popular evolutionary algorithm applied in research related to the optimization of construction scheduling (Hegazy 1999; Feng et al. 2000; Chan and Hu 2002). Apart from the single objective optimization, project managers may be simultaneously concerned with resource allocation and time/cost tradeoff before the implementation of construction works. Several multicriteria optimization models for searching the optimal combination of construction duration, resource amounts, and minimum project cost have been introduced (Leu and Yang 1999; Leu and Hung 2002).

Particle swarm optimizer (PSO) is another well known evolutionary optimization technique proposed by Kennedy and Eberhart in 1995 (Kennedy and Eberhart 1995). The basic idea of PSO is inspired by natural flocking and swarm behavior of birds and insects. PSO shares the ability of the GA to optimize arbitrary nonlinear functions, but boasts a much simpler implementation mechanism. While PSO requires less computational bookkeeping and generally only a few lines of code, it clearly demonstrates good possibilities for widespread use in electromagnetic optimization (Boeringer and Werner 2004). One recent research is that Zhang et al. (2006a and 2006b) applied the PSO technique in solving resource-constrained project scheduling problems. It is noteworthy that most academic researchers focused on the single construction site project in formulating resource scheduling problems. In this paper, we address the resource allocation over multiple, concurring building sites.

3 CONSIDERATIONS AND PRACTICES FOR BAR BENDERS JOB SCHEDULING

3.1 Technological Sequence

The technological sequence is defined as precedence relationships between construction activities. In general, constructing different reinforced concrete components such as foundation, slab or column entails slightly different technological sequence. For example, the activity sequence for erecting a column is fixing rebars, succeeded by installing the formwork, then by concreting. For concrete slab or beam construction, the sequence of installing formwork, succeeded by fixing rebars, then by placing concrete generally needs to be observed on one building cycle.

3.2 Repetitive Building Cycles

Repetitive building cycles at each site necessitate the allocation of skilled labor resources to handle their specialty craft activities on a periodic basis −for instance, fixing rebars on a number of repetitive building floors in constructing the superstructure of a high-rise at one site. Ideal scheduling will coordinate the building cycles at multiple concurring sites, so as to make full use of specialist labor forces under a subcontractor.

When the site is handed over from one specialist subcontractor to another, the main contractor or the client would not like to see any stoppage to progress on a building site. Thus, it is important to maintain the site work con-

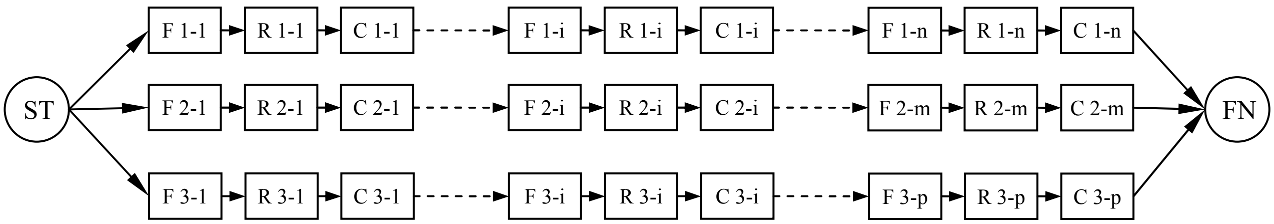

Figure 1: The repetitive building cycles on three construction sites

tinuity and reduce the chances of having idle days at one site due to labor resources being tied up at others. On the subcontractor's side, good job planning should ensure the site activity will not come to a halt due to a shortage in labor resource provisions.

3.3 Alternative Method Options

Alternative method options for tasking a building cycle at a specific site have different labor use requirement and time requirement. Identification of those options depends on site space available, experience and competency of laborers, and other factors relating to particular job conditions. For instance, given the same work content on one floor at a building site, it may take one bar bender five work days or two bar benders three days to finish. At the job planning stage, the subcontractor needs to determine the best combination of options at each site such that his resource utilization across all sites being handled is maximized and his overall time/cost performances improved.

3.4 Quantity of Skilled Laborers

The quantity of skilled laborers −the subcontractor needs to hire− constitutes the resource limit in his job planning. On one hand, hiring fewer laborers will cause resource shortage, resulting in site progress stoppage (due to unavailability of laborers) and prolonged project time. On the other hand, hiring excessive laborers will possibly lead to shorter job duration yet at the expense of increasing the total cost, particularly, the non-productive labor cost due to resource idling. This is a critical planning decision that should be weighed against resource utilization and overall time/cost performances.

3.5 Project Cost Determination

From the subcontractor's standpoint, the total cost of completing all jobs is an important issue during the project planning and scheduling phase. The project cost is manly classified into two general categories: direct cost and indirect cost. In addition, early completion incentive and liquidated damage would be included in the construction contract since the client often intends to motivate contractors to accelerate project progress and avoid schedule overrun. The total project cost is, therefore, to sum up direct and indirect costs, plus liquidated damage, and minus early completion incentive.

4 CASE STUDY

In this case study, a computer platform called the *Simplified Simulation-based Scheduling* (*S3*) system was tested for optimizing short term operations (about 60 working days) by a reinforcement subcontractor serving multiple construction projects. In practice, the job duty of a bar bender includes cutting, bending and fixing reinforcement steel bars according to drawings and bending schedules. Let's say a reinforcement subcontractor has three building sites, and each site has a number of building cycles (or floors), each associated with a particular sequence of building tasks. For the current case study, constructing slabs on building floors is of concern and the construction technology requires that the reinforcement task be done after the formwork is completed but before the concrete pour starts. For example, reinforcement for the first floor slabs commences after erecting the first floor slab formwork.

An activity-on-node diagram is given in Figure 1 to depict both the technological sequence constraints and the repetitive building cycles on three concurring sites. The quantities of building cycles at three sites are denoted with n, m, and p respectively. Task identification is indicative of activity ID ("*F*" short for formwork, "*R*" short for reinforcement, "*C*" short for concrete), site ID, and cycle ID in sequence.

In Table 1, the "site start time" represents the time when the main contractor hands over the site for the subcontractors to commence repetitive building floors at each site. The number of floors (working cycles) at each site is also known. The "Formwork cycle duration" and "Concreting cycle duration" at each site are estimated by the formwork subcontractor and the concrete subcontractor, respectively. The cycle duration represents job planning decisions and commitment by corresponding subcontractors. Besides, the proposed deadlines, early completion incentives and liquidated damages of all three sites are summarized in Table 1. The daily cost of laborer is $800. The indirect cost

Table 1: Project details of three construction sites in case study

Site	Site start time	No. of working cycles	Formwork cycle duration	Concreting cycle duration	Reinforcement cycle duration	Bar benders required	Contract deadline	Early completion incentive ($/day)	Liquidated damage ($/day)
1	0	5	3	4	5	5	62	5000	30000
2	0	3	6	5	8	5	58	5000	30000
3	3	3	6	3	7	3	55	3000	20000

of each site is assumed to be $1000 per day. Note all the dollar values in our current case study are given in Hong Kong Dollars (7.8 HKD is equivalent to 1 USD).

By running simulation experiments, the "what-if" scenario analysis can be readily conducted in order to assess and compare different scenarios, such as prolonging the duration on a specific activity, adjusting the resource configuration or activity priorities. Simulation and optimization experiments were performed on two key scenarios: the first scenario is to adjust the activity sequence and resource limits, and the second one is to evaluate the effects of different alternative method options on the basis of the outcome of the first scenario.

4.1 *S3* Simulation Model Setup

The *S3* system is customized on top of the simulation platform of *SDESA* which is developed by Lu (2003). As an enhanced version of the critical path method, the *S3* system allows resource, time and cost-integrated project scheduling analysis under resource-availability constraints. The details of *S3* model formation can be referred to Lam (2007) and Lu et al. (2008). To enable the current case study, two enhancements were made to the *S3* model definition. The first one is encoding the determination of the sum of project costs from multiple sites, and the second one is exerting decision control over selecting different activity method options during simulation. The details of *S3* model set up and enhancements can be found in the Appendix A at the end of this paper.

4.2 PSO Framework in *S3*

Based on a valid resource scheduling simulation, the particle swarm optimizer (PSO) can be integrated to automatically optimize the resource schedule. PSO follows a stochastic search strategy on a population of individuals, each representing a possible solution to the problem. Once the fitness values for all the members of the population are evaluated, a selection process is carried out where better individuals (higher fitness values) stand a greater chance to be selected for further evolution. The whole process is repeated over a number of evolved populations until some termination criteria is satisfied. The average fitness of the population is expected to improve over generations, and finally converge at the point close to the global optimum.

In this research, PSO is embedded in *S3* to decide on the optimal combination of the activity priorities for resource allocation, the optimal combinations of method options at each site (i.e. number of bar benders employed and associated cycle duration), together with the optimum resource limits, in order to attain the shortest project duration or the least project cost. The proposed PSO approach uses particles to represent the decision options in project scheduling. The problem's parameters in a *S3* simulation model are mapped to a PSO particle as shown in Figure 2. Given *n* being the number of activities, *p* as the type of resources, and *q* as the number of alternative method options, the multiple-dimension particle structure can be used to represent the potential solution to the *S3* model. By automatically adjusting the priority values for activities and limits of resources, *S3* will consider resource allocation and all precedence relationships simultaneously to obtain the total project cost in evaluating each particle of PSO.

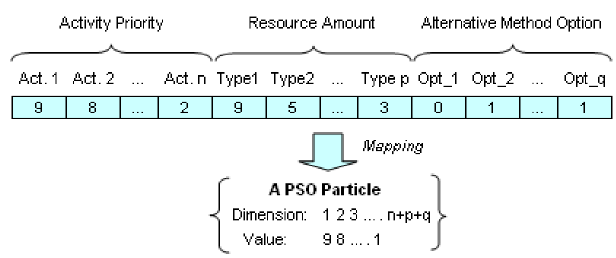

Figure 2: PSO particle mapping in *S3* model

4.3 Optimization Analysis 1: adjusting activity priority and crew size

For this example project, resource-availability constraints were applied on two scheduling tools (i.e. *P3* and *S3*). Note *P3* provides an option of automatic forward resource leveling following its built-in heuristic rules. The same activity execution sequence in resource allocation –as followed by *P3* provides an to *S3*. The activity which starts earlier in *P3* is assigned with a higher activity priority in the S3 model. As a result, given 10 laborers available, the cost of completing the jobs at all sites is $737,800. Since there is not enough manpower resources to carry out all the tasks on time, the project completion date of Site 3 (63 days) was 8 days behind the contract deadline (55 days) as illustrated in Figure 3.

From the standpoint of subcontractors, completing task on schedule is paramount to their reputation and competitiveness. The rebar specialist subcontractor, therefore, was willing to hire extra laborers to accelerate the overall

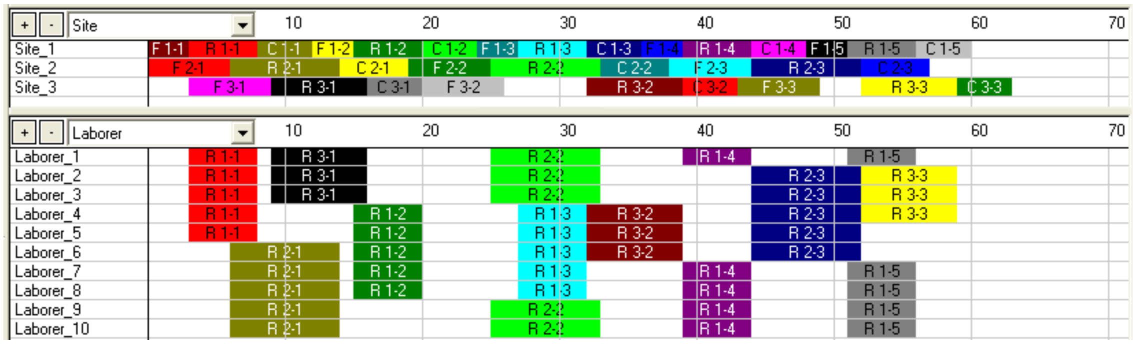

Figure 3: Activity bar chart and Resource bar chart for case study (Scenario 1: given 10 laborers)

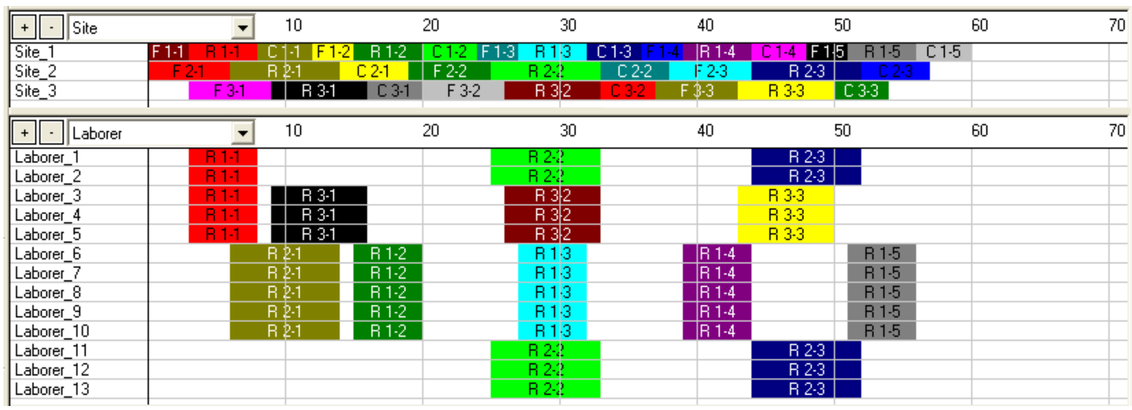

Figure 4: Activity bar chart and Resource bar chart for case study (Scenario 1: given 13 laborers)

working progress. Under such circumstance, the *S3* optimization objective could be set as minimizing the project cost bound by a specific range of resources. The quantity of laborers was set to be bounded on [10, 20] before optimization.

When the *S3* system reached the optimum state, it was found that a total of 13 laborers were needed to attain the high service level (i.e. zero site idle time due to lack of bar benders). Through the resource provision optimization, all three projects could meet the deadline and the total cost could be reduced to $609,000 (-17.5%) due to the project duration being shortened. The detailed laborer allocation schedule is shown in Figure 4, which could be followed by the subcontractor to assign his labor force of 13 to different sites.

4.4 Optimization Analysis 2: adopting alternative method options

In a second analysis scenario, the subcontractor needed to configure the most efficient crew size and specify the most suitable working progress on each site before the construction starts. He would also determine the best combination of alternative method options at each site such that his resource utilization across all sites being handled is maximized and his overall time/cost performances improved. As a result, allocating a limited amount of labor resources more efficiently in running operations over multiple sites would potentially bring in both quality and cost benefits.

Let us assume that the subcontractor hired a certain number of bar-bending laborers (10 laborers) on a relatively permanent basis. A laborer's productive time is distinguished from his non-productive time over the total job period. Note, laborers could do nothing on some days, because of the formwork or concreting activities being undertaken at sites. It is important to point out, however, that this waste in the use of resources is not caused by the laborers being intentionally idle. Rather, it is down to the subcontractor's inefficiency in scheduling the work. As such, the system allows the contractor to see the economic impact of the different combinations of alternatives on the resource allocation plan. In planning this kind of operations, the subcontractor's planner considers alternatives of getting the job done at each site: e.g. for one floor cycle at site 1, he could use 1 laborer for 4 working days or 2 laborers for 2 working days. In general, the larger amount of manpower, the shorter is the activity duration (reinforcement). In this case study, we assume there are two alternatives for each construction site as given in Table 3. In the corresponding *S3* model, the activity times will be crashed by adding extra laborers (the number of the corresponding resource "Normal Option" is set as zero in the *S3* optimization results.)

Table 3: Summary of reinforcement method alternatives

Site	Rebar Cycle duration (d)	Laborers required	No. of Resource "NL" in *S3* model	Remarks
1	5	5	1	Normal
	4	8	0	Crash (+3 LB)
2	8	5	1	Normal
	6	8	0	Crash (+3 LB)
3	7	3	1	Normal
	4	6	0	Crash (+3 LB)

Notably, the analysis aims to find out the activity sequence, resource crew size and combination of method alternatives that result in the minimum project cost. The quantities of laborers and the normal method option signal (i.e. "*NL-S1*") for each site were set to be bounded on [10, 20] and [0, 1] respectively before optimization. The *S3* solution suggests that the minimum total project cost of \$541,000 would yield when the method option combination is as follows: 5 laborers do one cycle for 5 days at Site 1; 5 laborers do one cycle for 8 days at Site 2; and 6 laborer completes one cycle for 4 days at Site 3. The resultant resource-activity matrix bar chart schedule is shown in Figure 5. Compared with the original scenario, the total cost of all projects deceases by 26.7% due to the reductions of non-productive cost of bar benders and liquidated damages.

Upon assessing analysis results from above two scenarios, the bar bender subcontractor can decide on the best strategy to his advantage.

5 CONCLUSIONS

The specialist subcontractor managers would like to find out the optimal numbers of manpower resources to be deployed together with an optimal schedule for carrying out the reinforcement tasks on multiple building sites, aiming at minimizing the total project cost under limited resource availability constraints being imposed. Therefore, we provided an approach to address the challenges in single-skilled labor resource management and scheduling over multiple concurring construction sites in this paper. Factoring in technological constraints, repetitive building cycles, alternative method options, and the limited quantity of skilled laborers, the simulation-based scheduling tool resulting from in house research can serve as an effective computer aid in helping the users to analyze and predict the performance of the complicated skilled laborer management planning and evaluate various scenarios postulated. In addition, the particle swarm optimizer (PSO)-integrated simulation platform will empower managers in formulating optimal decisions on project scheduling, thus enhancing productivity and resource utilization. In a case study of bar-bender scheduling over three sites, we described the input variables, the constraints, the optimization variables, together with the scheduling results, which indicate that our simulation-based method is capable of producing valid project schedule outputs that are resource, time and cost-integrated, given different combinations of resource limits and method options. Besides, the optimization engine in search of the best combination of construction methods at individual sites and the optimum size of labor force could yield the least costly, most productive resource configuration and schedule, which are instrumental in managing the skilled labor resources available and meeting demands at a number of building sites. Compared with the original scenario that followed by *P3*'s resource leveling results, the total cost on all projects would decease by 26% if the optimum resource crew size and alternative method options were implemented. In conclusion, the simulation and optimization-integrated tool like *Simplified Simulation-based Scheduling* (*S3*) system is found capable of assisting a project manager in configuring the least costly, the most productive manpower resources so as to enhance the utilization level of the laborer resources available while meeting activity demands at multiple construction sites.

ACKNOWLEDGMENTS

The research presented in this paper was substantially funded by an internal research grant of the Faculty of

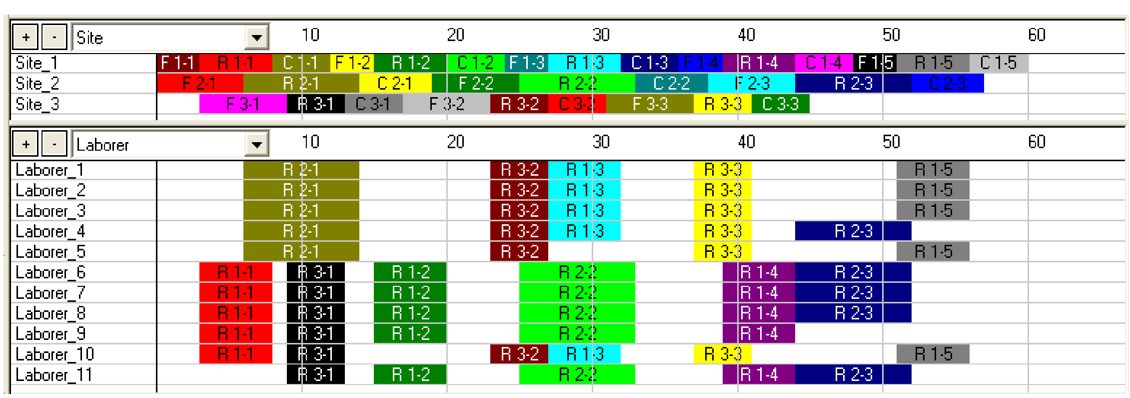

Figure 5: Activity bar chart and Resource bar chart for case study (Scenario 2: given 11 laborers)

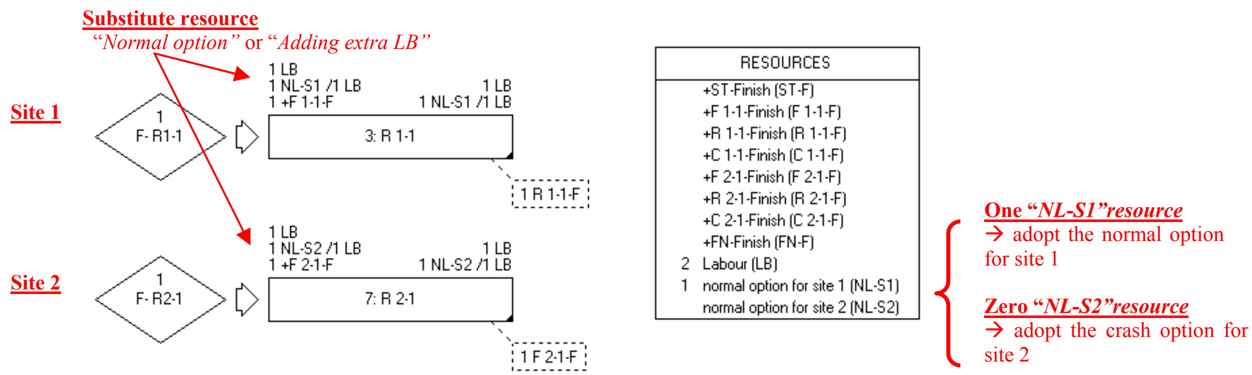

Figure 6: Processing information of *S3* model

Construction and Land Use, Hong Kong Polytechnic University for promoting cooperation with the University of Maryland. We especially express thanks to Dr. M. Skibniewski, the University of Maryland, for his efforts in facilitating research exchange in construction engineering and management between Hong Kong and US.

APPENDIX A

The in-house developed *Simplified Simulation-based Scheduling* (*S3*) system is customized on top of the simulation platform of *SDESA* which is developed by Lu (2003). As an enhanced version of the critical path method, the *S3* system allows resource, time and cost-integrated project scheduling analysis under resource-availability constraints. In this experiment, two modifications are required for the *S3* system to conduct this case study.

Firstly, *S3* features the determination of total project cost by calculating the direct cost, indirect cost, early completion incentive and liquidated damage for each site according to the corresponding resource provisions and project durations. The direct cost includes resources' productive cost and resources' non-productive cost. According to the resource allocation results, *S3* obtains the start time and finish time for all the resources and then calculates the corresponding productive and non-productive costs.

Secondly, *S3* is exerting decision control over selecting different activity method options during simulation. In the *S3* model, we can specify the resource requirements for each activity. Note, the availabilities of resources of all types combine to specify the prerequisite conditions for executing one activity. For the case study, the activity duration can be modified by adding extra resources while the judgment of the activity method is based on model specifications using internal substitute resources and resource attributes as provided in the *S3* model. The details are shown in Figure 6. The Reusable Resource Entities (such as manpower and equipment) requested by each activity are marked on the top left corner of the activity rectangle. Note in Figure 6, both activities "*3:R1-1*" and "*7:R2-1*" have higher priority to capture resource entity "*Normal option for site 1 (NL-S1)*" and "*Normal option for site 2 (NL-S2)*" respectively. Only in case "NL-S1" or "NL-S2" is unavailable, the resource entity "*Labour (LB)*" will be seized. At the end of the activity, any Reusable Resource Entities to be released back to the resource pool are marked on the right corner (in Figure 6). In the resource pool of the *S3* model as shown in Figure 6, two laborers are defined as the maximum daily limit for the labor resource while the quantities of resource entities "*Normal option for site 1 (NL-S1)*" and "*Normal option for site 2 (NL-S2)*" are set as one and zero, respectively. According to this resource limit input, Site 1 will adopt the normal method option to carry out the reinforcement activity (i.e. using one laborer only), but Site 2 will require one extra laborer resource (the substitute resource "*1 LB" as specified in "1 NL-S1/1 LB*") in order to crash the activity.

REFERENCES

Boeringer, D. W., and Werner, D. H. 2004. Particle swarm optimization versus genetic algorithms for phased array synthesis. *IEEE Transactions on Antennas and Propagation*, 52(3), 771-778.

Chan, W. T. and Hu, H. 2002. Production scheduling for precast plants using a flow shop sequencing model. *Computing in Civil Engineering*, 16 (3), 165-174.

Feng, C. W., Liu, L., and Scott, A. B. 2000. Stochastic construction time-cost trade-off analysis. *Computing in Civil Engineering*, 14(2), 117-126.

Galloway, P. D. 2006a. Survey of the construction industry relative to the use of CPM scheduling for construction projects. *Construction Engineering and Management*, 132 (7), 697–711.

Galloway, P. D. 2006b. Comparative study of university courses on critical-path method scheduling. *Construction Engineering and Management*, 132 (7), 712–722.

Harris, R. B., and Ioannou, P.G. 1998. Scheduling projects with repeating activities. *Construction Engineering and Management*, 124(4), 269-278.

Hegazy, T. 1999. Optimization of resource allocation and leveling using genetic algorithms. *Construction Engineering and Management*, 125(3), 167-175.

Hegazy, T., and Wassef, N. 2001. Cost optimization in projects with repetitive nonserial activities. *Construction Engineering and Management*, 127(3), 183-191.

Kennedy, J., and Eberhart, R. 1995. Particle Swarm Optimization. *Proceeding of IEEE International Conference on Neural Networks*, 4, 1942-1948.

Lam, H. C. 2007. Resource-constrained project evaluation and review technique (PERT): stochastic simulation and optimization. *Thesis of Master of Philosophy*, Department of Civil and Structural Engineering, Hong Kong Polytechnic University.

Leu, S. S., and Hung, T. H. 2002. A genetic algorithm-based optimal resource-constrained scheduling simulation model. *Construction Management and Economics*, 20, 131-141.

Leu, S. S., and Yang, C. H. 1999. GA-based multicriteria optimal model for construction scheduling. *Construction Engineering and Management*, 125(6), 420-427.

Liberatore, M. J., Pollack-Johnson, B., and Smith, C. A. 2001. Project management in construction: Software use and research directions. *Construction Engineering and Management*, 127(2), 101-107.

Lu, M. 2003. Simplified discrete-event simulation approach for construction simulation. *Construction Engineering and Management*, 129 (5), 537–546.

Lu, M., Lam, H. C., and Dai, F. 2008. Resource-constrained critical path analysis based on discrete event simulation and particle swarm optimization. *Automation in Construction*, 17, 670–681.

Reda, R. 1990. RPM: Repetitive project modeling. *Construction Engineering and Management*, 116(2), 316-330.

Yamin, R. A., and Harmelink, D. J. 2001. Comparison of linear scheduling model (LSM) and critical path method (CPM). *Construction Engineering and Management*, 127(5), 374-381.

Zhang, H., Li, H., and Tam, C. M. 2006a. Particle swarm optimization for preemptive scheduling under resource-constraints. *Construction Engineering and Management*, 132(3), 259-267.

Zhang, H., Li, X., Li, H., and Huang, F. 2006b. Particle swarm optimization-based schemes for resource-constrained project scheduling. *Automation in Construction*, 14, 393-404.

AUTHOR BIOGRAPHIES

HOI-CHING LAM received his B. Eng degree of Civil and Structural Engineering, M. Phil. degree from the Hong Kong Polytechnic University, and now is a Research Associate of Department of Civil and Structural Engineering at the Hong Kong Polytechnic University, working on model simulation and optimization, along with construction management. His email address is <ceching@polyu.edu.hk>.

MING LU is Associate Professor of Construction Engineering & Management of the Department of Civil and Structural Engineering, the Hong Kong Polytechnic University. He received a Ph.D. degree from the University of Alberta, Canada. His research interest is development of easy-to-apply, cost-effective methodologies of artificial intelligence and computer simulations for construction engineering and project management. Dr Lu proposed the Simplified Discrete-Event Simulation Approach (SDESA) for construction simulation and has led the research effort of developing the SDESA computer platform. His email address is <cemlu@polyu.edu.hk>.