Multiproject Planning and Resource Controls for Facility Management

E. William East[1] and Liang Y. Liu[2]

Abstract: Facility managers face the challenges of managing many different types of small, geographically dispersed construction projects. Depending on the complexity and distribution of projects, the time required to prepare for production consumes a large percentage of the total time required to complete the job. Increasing crews' productive hours is a key objective when planning multiproject schedules. Existing methods, however, lack the effective means to explicitly model, analyze, and optimize resource utilization for these multiple concurrent projects. As a result, few facility managers fully exploit the potential to better manage their often limited budget and resources. This paper presents an explicit model of the mobilization requirements of multiple crews performing a variety of different activities over a geographic space. The model allows the facility manager to explicitly investigate the impact of crew composition, crew specialization, and depot locations. Using work rule decisions regarding alternative crew allocations, facility managers may dynamically allocate resources to optimize resources and to complete projects in a minimum amount of time. To verify and validate this new model, a computerized system, called FIRS (Facility/Infrastructure Resource Scheduler), was created to analyze the multiproject resource plans with data from two military organizations and a university campus. FIRS utilizes a new genetic algorithm that was developed specifically to work with multiproject scheduling. Using FIRS, facility managers can develop and test alternative crew allocations based on the qualifications of the crews available and the type of operation being performed.

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Introduction

One of the most challenging tasks facing project managers responsible for facility operation and maintenance is efficiently planning and controlling the execution of a dynamic set of construction projects while not exhausting an organization's limited resources. Large organizations, both governmental and private enterprises, often own a large number of facilities. These organizations, such as public agencies, college campuses, military installations, utility companies, schools, and highway administrations, all face the challenges of prioritizing project activities and controlling resources with limited time, budget, and manpower.

Since resource allocation decisions are currently made by individual shop foremen who do not have complete knowledge of the actions of other foremen, the execution of these plans is not as efficient. Anecdotal evidence suggests that at least 10% of the resources available to the facility manager are wasted due to workers arriving to the job site before prerequisite work has been completed (East 2005). Efficiencies could also be gained from sequencing multiple projects in the same, or related, physical locations to eliminate duplicated work contained in individual projects. A complicating factor of this class of problems is that the time required to physically complete the work may be less than the mobilization time required to prepare to complete the work. As a result, a significant portion of the total cost of project execution is not "wrench time." Projects must be accomplished within the funding and manpower levels allocated to the facility management office. Construction budgets and limitations of available material, labor, and equipment impose severe restrictions on project managers. One of the most visible examples of insufficient infrastructure funding is published by the American Society of Civil Engineers, Infrastructure Report Card (ASCE 2005).

A general diagram of the facility/infrastructure resource scheduling problem is shown in Fig. 1. In a centralized planning regime, decisions are made by the facility manager, shown in the middle of Fig. 1. The facility manager uses available resources, within management constraints, to complete a dynamic set of customer-requested projects. To communicate his plan to customers, a project management plan identifies the schedule for each project which contains tasks to be completed by workers. An effective methodology and tools are needed to allow facility managers to quickly and effectively allocate material, labor, equipment, and budgets. This improved allocation will result in the completion of more noncritical—but vitally important—jobs, leading to a decrease in the long-term cost of maintenance and improved quality of infrastructure and facilities.

Existing Research

Current research into the general construction resource allocation problem may be broken down as shown in Fig. 2. The majority of

[1]Research Civil Engineer, U.S. Army Corps of Engineers, Engineer Research and Development Center, Champaign, IL 61826-9005. E-mail: bill.east@us.army.mil

[2]Associate Professor, Dept. of Civil and Environmental Engineering, Univ. of Illinois at Urbana, Champaign, Urbana, IL 61801. E-mail: lliu1@uiuc.edu

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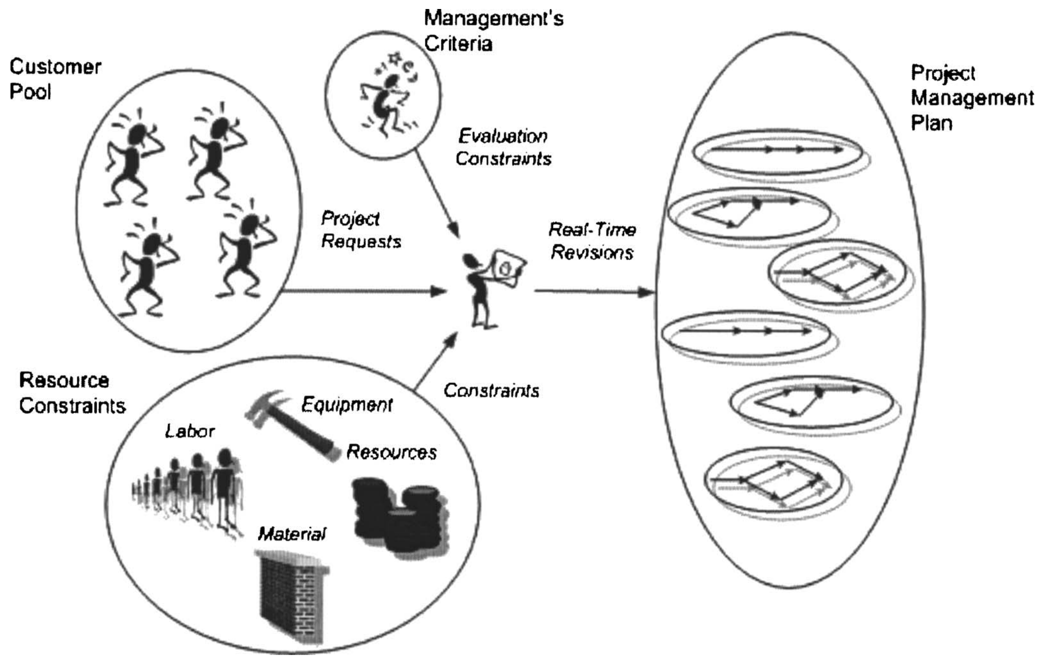


Fig. 1. Resource allocation domains

work to date has focused on tools for individual project managers working on single large projects. Consideration of large sets of multiple projects, outside of a specific program of construction for a given client, location, or program of construction, is not typically considered due to the dynamic nature of cross-project constraints. A full evaluation of the multiple-project domain (Blismas et al. 2004) is, however, critical since the majority of participants in the construction industry must complete multiple simultaneous projects (Turner and Speiser 1992).

Many applications of heuristic approaches to large single projects may be found in literature (Mosehli and Lorterapong 1993; Ozdamar and Gunduz 1995; Davis 1975). The focus of the activity level schedules is the interaction of sequence among tasks; resources are assumed to be interchangeable. Simulation and other tools may be used to model small critical segments of these projects to evaluate alternative construction methods. Simulations provide an "operational" level of task breakdown that stochastically defines differences among crew behavior (Halpin and Woodhead 1976).

Exact methods of solving small problems require a good representation to reduce the computational burden on the branch-and-bound algorithm. Often, one problem formulation requires many additional equations to restrict noninteger aspects of the problem sufficiently to provide a solution. By the time such a model has been created, the conditions under which the schedule has been developed are no longer valid. Combinatorial problems

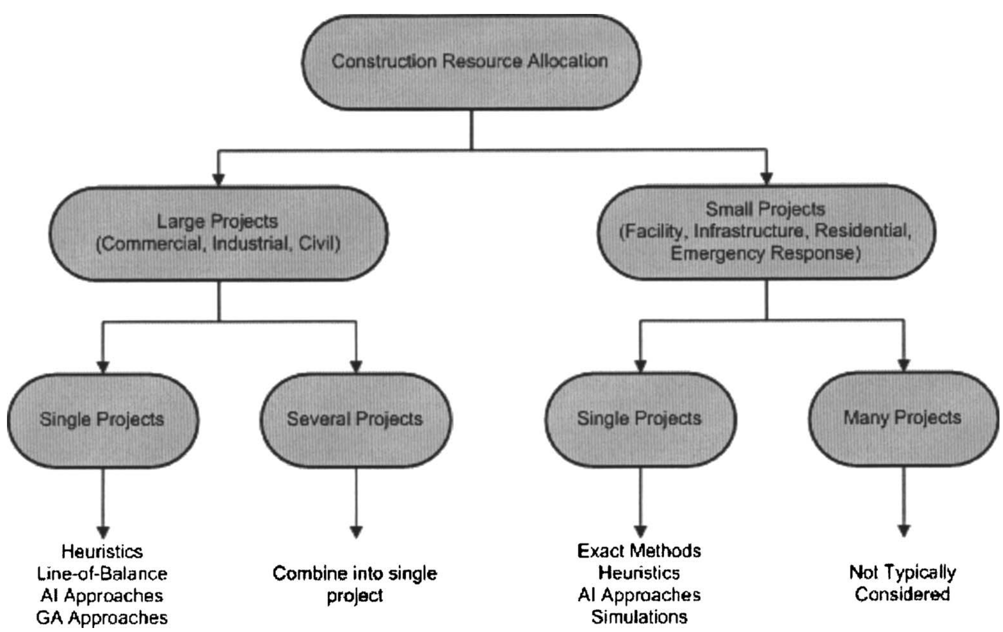


Fig. 2. Problem domain structure

J. Constr. Eng. Manage., 2006, 132(12): 1294-1305

associated with exact solutions add to the time required to develop a solution. The solution acceptable to a facility and infrastructure manager must have a firm correlation with physical elements of the work order operations to be completed. This correlation is needed since the project manager must be able to evaluate the current plan based on rapidly changing requirements, which cannot be defined mathematically as constraints in exact methods. A more general criticism of mathematical programming techniques is that these approaches attempt to develop objective decisions in situations where decisions are often anything but objective (Holloway 1979).

Knowledge-based, or expert, systems have proven to be useful in assisting researchers in the understanding of a wide variety of domains. These domains may be characterized as those in which system inputs and outputs are relatively stable over many years. As the requirements of such a system vary from the initial design parameters, the system will become less useful. As with mathematical programming approaches, knowledge-based approaches also have problems with limiting the number of possible answers that must be evaluated (Cohen and Feigenbaum 1982). In both types of approaches, the application of problem-specific constraints is vital to limiting the search space (Hassain 1993).

Neural network approaches appear to be less fragile, in terms of missing or incorrect input data, than are expert systems. However, these systems require the researcher to recreate the entire problem in terms of input and output nodes and provide valid cases for the model to be developed. While they are very useful for domains requiring classification of static or near-real-time data streams, these systems do not appear to be as useful in providing a prescription for action that should be taken in a changing environment.

Genetic algorithms (GAs) have demonstrated promising results, where a directed solution space search, combined with very simple operators, may avoid standard hill-climbing problems. GAs may find the common ground, or "saddle points," between multiple objectives that are often dominated by individual aspects of complex objective functions. Rather than providing a single correct solution, GAs are able to identify multiple optimal or near-optimal solutions (Chan et al. 1996; Grobler et al. 1995; Hegazy et al. 2004; Leu and Yang 2000).

Research Objectives, Scope, and Assumptions

Built upon the capability and promise of GAs, this research aims at reducing the cost of infrastructure and facility management projects through improved project planning. To accomplish this goal, the following areas were investigated: Crew mobilization to support nonrepetitive multiproject schedules, crew assignment based on work rules, representations for nonwork tasks, and near-optimal simulations of the multiproject scheduling domain. To clearly define the work to be conducted, assumptions regarding components of the domain were made. These assumptions, described in the following sections, included the nature of facility management projects, the level of detail required for project breakdown, the resources needed to accomplish project tasks, and the way that project plans are created and evaluated.

Projects

In facility project management settings, where maintaining physical plants or buildings is of the greatest concern, facilities are identified at discrete locations in a distributed geographic space. While renovation programs may include multiple facilities, in this research, projects were defined at specific locations so that remobilization would not be required to complete the entire project. Projects in facility management domains are completed within otherwise operational facilities. Disruptions to these facilities must be kept to a minimum. In this research, projects will start and finish as soon as possible, minimizing disruptions to existing operations. Some projects must be accomplished immediately for life-safety issues, while others should be accomplished quickly due to task importance, promised delivery dates, or other external constraints. Other projects are of low priority, and may be accomplished as crew availability permits. Project managers frequently talk about projects in terms of relative bands of priority. One example of priority bands are projects categorized into "emergency," "critical," "normal," and "low-priority" sets. This research addresses the use of these priority bands. One definitive measure of priority is user-required finish dates. This research allows managers to model such user milestones. Incentives and penalties for missing these milestones are also addressed in this research.

Activities

Unlike traditional construction scheduling, facility/infrastructure projects have durations that generally do not exceed a few days. In most cases, task durations are measured in hours or minutes. One challenge in modeling the relatively short task durations is that certain nonproductive tasks must be considered when creating project activities. Nonwork activities, such as concrete curing or paint drying must be included since the duration of these activities may exceed the production duration. As a result, mobilization—the type of work performed by crews but not typically included when scheduling large projects—must be explicitly modeled and analyzed. Since the time required to gather materials and travel between jobs may be longer than the time to complete the activity once on the site, tracking crew mobilizations is a critical aspect of this research.

Crew Resources

In traditional construction projects, several similarly skilled workers are usually considered a crew. Traditional scheduling also assumes that materials are delivered on site and all tools required to complete the assigned task are provided. This is often not the case in the facility management domain. Due to the small quantity of work in facility management projects, crews are defined by one or two workers and a vehicle. Small tools are included on the vehicle as are all materials required to complete the project. Crew composition may change over time; however, for a given project plan, crews are considered indivisible as most crews in facility management domain are small with only a few skilled laborers. Each crew is assumed to carry the needed materials to the work areas. Consequently, crews capable of performing different types of work may need to change material inventory and small tools between projects. This research assumes that the type of materials required for different activities can be modeled. Depots are provided to allow crews to change material and on-board equipment as required to accomplish the planned work. Since crews are individually identified in this research, crew specializations are identified, and each crew may have different productivity based on the specific work type being performed. Large equipment or machinery, not normally part of a crew's inventory, may be included in a project plan as separate activities.

J. Constr. Eng. Manage., 2006, 132(12): 1294-1305

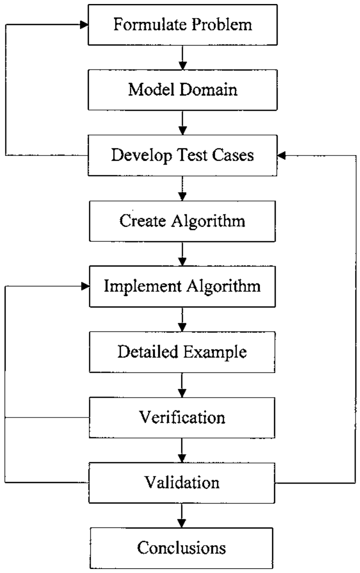


Fig. 3. Research methodology

Decision Criteria

This research assumes that project managers have fixed budgets that cannot be exceeded; therefore, a relevant objective function is cost minimization. In this research, it was assumed that the cost to perform each project can be quantified, calculated, and compared.

Research Methodology

To accomplish the aforementioned research objectives and scope, an iterative process was conducted following the methodology illustrated in Fig. 3. The first step in the research methodology is the problem formulation phase. Arguably, this step is the most important in the entire process, since it is the detailed formulation of the problem that leads to the remainder of the steps. In the problem formulation phase, the overall problem domain and relevant previous research were evaluated for potential areas of opportunity. Several facility managers participated in the process to ensure that meaningful problems and realistic assumptions are formulated regarding the domain.

The problem addressed in this research is how to near-optimally allocate limited resources, at the least cost, to multiple geographically dispersed projects, such as those found in facility/infrastructure management domains. The objective of the domain modeling phase is to identify the independent and dependent variables required to fully address the problem. A modeling method commonly used in the development of information systems, the unified modeling language (UML) (Booch et al. 2000), is applied to document this domain model. The UML provides a broad suite of system modeling tools that allow the modeling of object-oriented information systems.

Beginning with a very general model of the multiproject resource allocation problem, an initial domain model was revised several times during the course of this research. Use of real-world test cases, rather than bench testing alone, assists in developing of the model and defining the specific approach required to apply the model to the domain through the creation of an algorithm. The algorithm is used as a proxy through which the assumptions and hypothesis of the research are tested. To ensure that the algorithm most closely represents the model, detailed examples and verification steps are conducted. To determine the validity of the hypothesis, as described in the algorithm, test case data are applied to the algorithm during the validation step. Results from experimentation during the validation stage allow conclusions to be drawn and documented.

Domain Modeling

The domain model was developed to investigate the impact of individual crew mobilizations and specializations, and the interaction of work rules on crew formulation. Key to this formulation is the identification of how these individual factors were defined within the domain, which factors were under the control of the facility manager, and which factors were a byproduct of facility manager decisions. Domain factors modeled during this research included the type of work that could be performed by different crews. The basic unit of crew formulation in this domain is one work item and one vehicle. This crew carries with it all materials and equipment necessary to complete the assigned operation. Crew formulation is accomplished by a shop foreman and typically does not vary widely. The formulation of crews may be modeled for many days. If, however, the crew is assigned to multiple types of work, then at some point the crew will need to restock materials.

One of the key contributions of this research is the development of a general model for crew mobilization in facility/infrastructure domains. It turns out that mobilization and travel time are byproducts of the facility manager's crew allocation decisions. In this model, the time required to execute nonwork activities is added to each crews' list of activities based on each individual crew's current and future location and work type. These activities are added to the set of activities to be accomplished by the crews' set, and iteratively modify the resulting overall project schedule. To illustrate this, Fig. 4 contains an outline of the domain model used in this research. The Work Order Package allows incoming requests for work to be broken down into one or more individual projects. Each project consists of one or more activities, as shown in the Activity Package. Based on an Activity's Work Type, Crews are allocated to perform the required work through the classes in the Allocation Package. The model developed for this research provides a critical bridge between standard critical-path method (CPM) models for large individual construction projects and discrete event simulation models for construction operations. The model developed provides an operational-level schedule, while maintaining the commonly used CPM concepts of "project" and "activity."

Test Cases

Data from three sources were evaluated to create project test cases for this research. The first source considered was data from the University of Illinois Operations and Maintenance (O&M) shop (University 2004). Among other things, the data system used by O&M allows the creation of work orders, and tracks the completion of these work orders. The overall objective of the O&M software is to provide a given facility/infrastructure application, on the extent of unionization, and in-house work force capabilities. In union shops, work rules clearly define the operations that may be accomplished by types of crew shops. As a result, crews are modeled, in this research, based on the type of

J. Constr. Eng. Manage., 2006, 132(12): 1294-1305

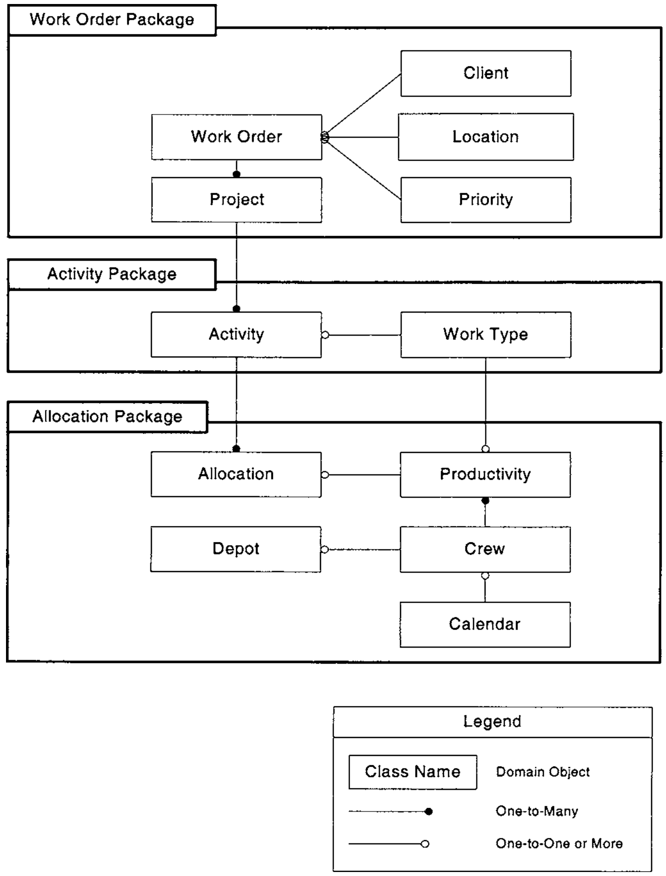


Fig. 4. Model overview

work that may be performed by each individual crew. A byproduct of such a representation is that historical crew performance may be monitored to reflect crew specializations.

Another domain factor, typically outside the purview of the facility manager, is the physical location of projects across a facility and, for a given project plan, the location of depots where crews may return to replenish or restock materials. As with crew formulation, the physical layout and depot location are inputs to the model. Given that crews are able to accomplish specific types of work at historically derived productivity rates, activity definitions in the model are made at an operational level. Thus, an activity is defined, in this model, by the quantity of work to which a predefined set of crews may be applied. The description of which activity contains which type of work is called, in this research, a "work rule." The work rules for each crew link the type of work performed in an activity with the applicable set of crews, and the productivity rate for the crew and that specific type of work.

While the facility manager's domain has many complex interactions, the project manager's decision may be simply stated. The facility manager's job is to efficiently assign crews to work. A side effect of the set of allocation decisions required to complete a given set of projects is that the mobilization requirements for the crews are defined by the routing of each crew through the projects. If a crew is assigned to the same type at several locations throughout the day, they load the truck with the required materials, travel to each operation according to their schedule, and complete the work. Interior painting is an example of a type of work where crews may perform the same operation (including paint color) in many spaces over a period of financial tracking against budget targets. To support this objective, work order costs are summarized against cost accounts that relate to specific O&M shops. As a result of the financial focus of the O&M system, data about the specific scope of individual work orders are not readily available through standard interfaces to the database used by O&M.

The second data source considered for use in this research was provided by the Army Research Laboratory (ARL) facility in Adelphi, Maryland (U.S. Department of the Army 2002). The facility management office at this laboratory uses the Maximo software system (MRO 2004). Maximo is an integrated maintenance office software suite. The laboratory facility office uses Maximo to schedule and track preventative maintenance activities of its staff. As a result, the information in ARL's database pertains to small "service order" projects. These very small projects are accomplished by individual workers throughout the facility. Since modeling these projects could be accomplished using vehicle routing problem domains, the data in this database were not used as the basis for development of test cases.

The Integrated Facility Systems (IFS) database provided by the Department of Public Works (DPW) at Fort Gordon, Georgia ultimately provided the most detailed information about specific facility management projects. IFS is the approved army standard system for automation support of DPW within the U.S. Army (U.S. Department of the Army 2004). This database contained a complete snapshot of both the "service orders" and "work orders" performed by the DPW. A detailed evaluation of the annual production of the DPW was conducted to develop a large pool of projects from which individual test cases were created.

Algorithm Creation

At a given point in time, a facility manager has a specific set of projects to complete with a known set of crews. The project manager would like to complete these projects in the least costly manner. Not knowing which method is the least costly, the project manager is limited to controlling cost by making two simultaneous decisions. The first decision is the order in which projects are to be accomplished. The second is to decide which crews should do what work.

Solution Space

Based on some simple examples, one can quickly arrive at a formula that describes the solution space of the facility/ infrastructure domain model. Assume that there are three projects, each of which has two production activities. Additionally, assume that there are two crews that can, alone or in combination, perform each of the three activities. For the three-project example, the evaluation of the number of total solutions begins with considering the number of combinations of crew assignments that may be made on a given activity. Since a given task may have Crew A, Crew B, or Crew A and Crew B allocated to it, there are three possible combinations for each crew. To determine the number of combinations of more than one activity, one combines the product of each combination. In the case of the six activities with three crew assignments possible, the total number of assignments is 36,729.

Now that the number of possible crew combinations has been determined, the number of project combinations can be evaluated. Since all projects must be completed in some order, the number of combinations of projects is the total number of permutations of

J. Constr. Eng. Manage., 2006, 132(12): 1294-1305

$$\prod_{x=1}^{i} c_x \times p!$$

i = total number of production activities

c = number of crew combinations for given production activity

p = number of projects

Fig. 5. Solution space formula

the order of the projects. The factorial of the number of projects provides the number of possible combinations. It then follows that, for our example set of three projects, there are $3! = 6$ possible permutations.

Combining the crew assignment combinations and project priority permutations provides that, for each permutation, there is one set of crew assignments. As a result, the total number of solutions for the example is 36 crew combinations for each of the project permutations, in this case 3!. The resulting figure is 4,374 combinations. Fig. 5 formalizes the solution space example, for the general case.

The implication of Fig. 5, on realistically sized problems, very effectively demonstrates the effect solution space size—reflected in so-called nonpolynomial (NP) problems (Ibaraki and Kotoh 1988). Given such a daunting task, it is clear why facility/infrastructure project managers do not have any interest in centrally managing small-works projects.

Genetic Algorithm Formulation

A GA is one class of algorithms demonstrated to effectively search NP spaces (Whitley 2004) and assumes that solutions to large problems may be described and then broken down into "building blocks." The power of the GA is that simultaneously considered solutions evaluate many subareas of the solution space. The goal of recombinant GA processing is to identify better-than-average building blocks, and recombine them to develop improved solutions (Goldberg 1998). The GA applied to this problem utilized an innovative fast messy-GA formulation (Goldberg et al. 1993) combined using relative order permutation, or "random keys," ordering (Norman and Bean 1997). The algorithm is called the Facility/Infrastructure Resource Scheduler (FIRS). The Ordering Messy Genetic Algorithm (OMEGA) is an example of the use of the fmGA in the context of a permutation problem (Knjazew 2002). The first component of the FIRS GA model was project priority. To model crew assignments, the specific assignments of each crew to each operation were specified. To ensure that the messy-GA formulation did not overallocate crews, an additional component—crew assignment count—was added to the decision variable representation in the FIRS algorithm.

Algorithm Inputs and Outputs

The algorithm implements the domain model and allows the simulation of alternative project manager domain formulations. Inputs to the project manager, "Management Constraints," "Customer Requests," and "Resource Constraints," (shown previously in Fig. 1) are translated into computable data inputs. The project manager's output, a "Project Plan," fully describes how crews are to be moved through the site to complete the required work. Management constraints imposed on the domain have been translated into the work rules that identify the set of all possible crews that may be allocated. The customer request input has been translated into a set of projects and activities that, when completed, will meet the customer's requirement. The resource constraint input is comprised of components: A list of crews available to complete the work based on the work rules identified by management constraint, and a description of the physical layout of the facility.

Given the static inputs provided, the algorithm simulates the project manager's decision-making process. The first decision the project manager makes is the order in which projects are to be accomplished. The second decision made is that of crew allocation to specific activities. Once these two decisions have been made, the resulting project management plans can be created.

The algorithm outputs are two tools to allow the project manager to communicate his/her plan to meet the customers' requirements. The first tool is a schedule of project completion. This schedule may be used for external communication to let customers know when to expect their work to be completed. The second output tool is a crew schedule that tells the crew where to go and what to work on, so that the customer's schedule may be met.

Algorithm Overview

The FIRS algorithm, shown in Fig. 6, is organized around the fast messy-GA approach. There are three essential steps in the fast messy-GA. The first step is the initialization of a fully defined population of solutions based on standard GA population sizing rules (Goldberg et al. 1992). This step is shown in Fig. 6, Step B.1. The best solution in the initial population is used as the standard of comparison, or "competitive template," during the next two steps of the process.

The second fast-messy GA step is to identify above-average fitness building blocks within the full solutions. This step is shown in Fig. 6, Step B.2. This is accomplished by randomly deleting portions of the solution, and using the competitive template to backfill underspecified solutions.

The third step is the recombination of above-average building blocks. This step is shown in Fig. 6, step B.3. This step is similar to that of the traditional GA. Initially, during this "juxtapositional" phase, small-order building blocks are spliced together. As the length of the string increases due to splicing, the cut operator ensures a reasonable size chromosome. Over-specification is controlled to ensure solution feasibility.

There are two loops which govern the processing of the GA. The inner loop, identified by Part B of Fig. 6, provides an initialized solution and drives that solution to convergence. The second loop—the outer loop—ensures the correct resetting of genetic algorithm parameters during each reinitialization.

FIRS was developed using a suite of commercially available programs (East 2005). FIRS was written in Visual Basic .NET with additional system libraries are required to link together MS Project and MS Access using the Object Linking and Embedding Automation (Microsoft 2005).

Fitness Function

During the processing of the search algorithm, a method was needed to evaluate and compare various project plans, based on different work sequence and crew assignments. The portion of FIRS that evaluates the impact of alternative crew allocation decisions, made by the search algorithm, is called the fitness function. In FIRS, the fitness function calculates the direct, indirect, and penalty costs of each project plan. This cost includes both the direct cost of the product work and the cost of mobilization and

J. Constr. Eng. Manage., 2006, 132(12): 1294-1305

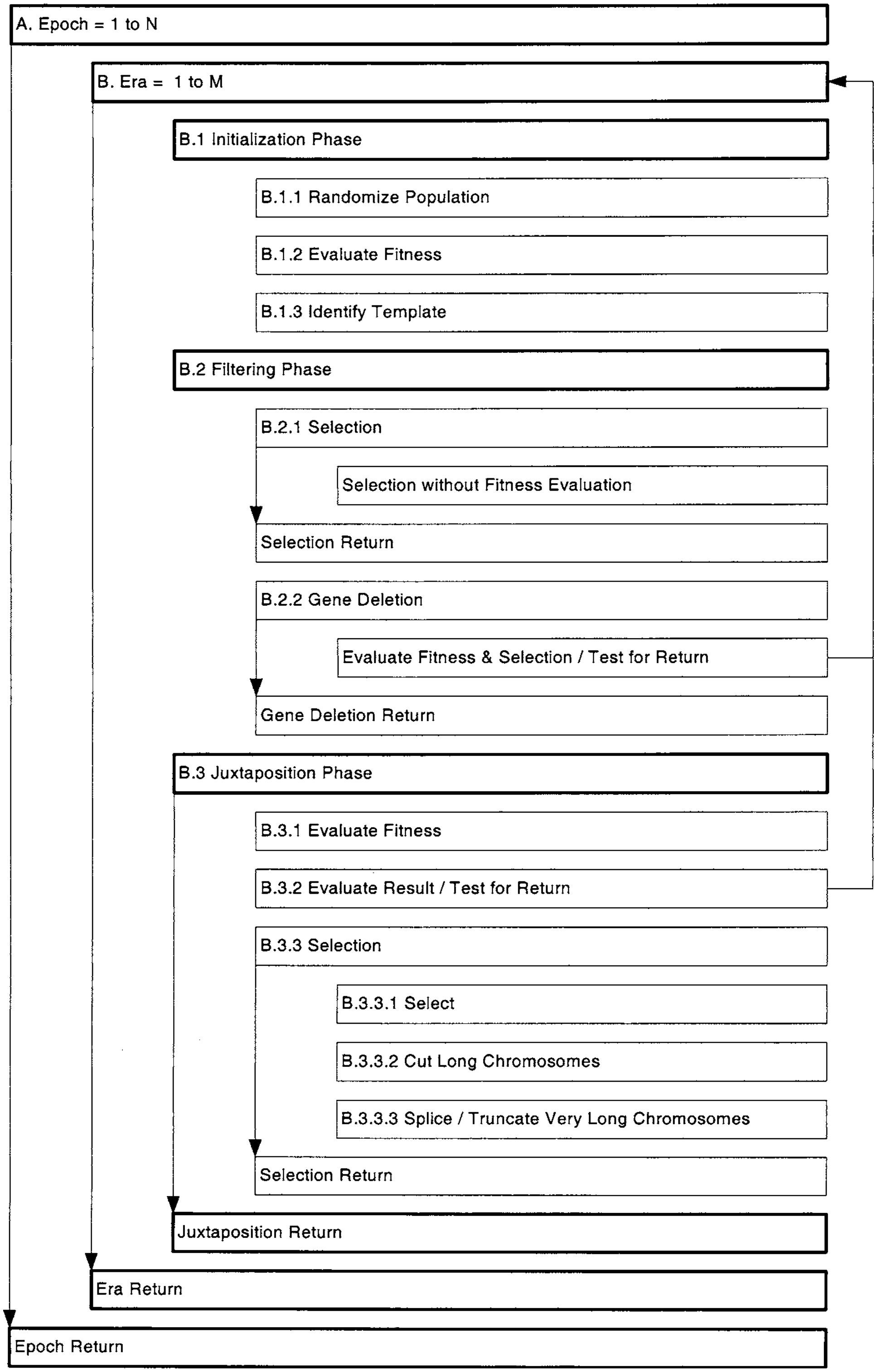


Fig. 6. FIRS search algorithm

travel time. Since there is an interaction between the crew allocation decisions and the mobilization and travel time required to accomplish those allocations, an iterative visually oriented fitness function was created. Fig. 7 illustrates the FIRS Fitness Function.

The evaluation of the cost of each project plan begins with a determination of the direct costs of the allocation decisions made by the facility manager, simulated by the GA search algorithm in FIRS. Given the list of projects and activities, geographical distribution of projects, and crew productivity rates for specific types of work to be accomplished, the initial duration of each activity is calculated based on the quantity of work (provided as part of the default data) and the sum of the productivity rates for each of the assigned crews. Given the default activity duration, the schedule may be leveled to ensure that crews are available to perform the required operations shown in Fig. 7, Step C. The resulting MS Project schedule is shown in Fig. 8. Leveling is conducted using the algorithm provided by MS Project, based on the priority of the project and the early start time of each activity. Priority leveling

J. Constr. Eng. Manage., 2006, 132(12): 1294-1305

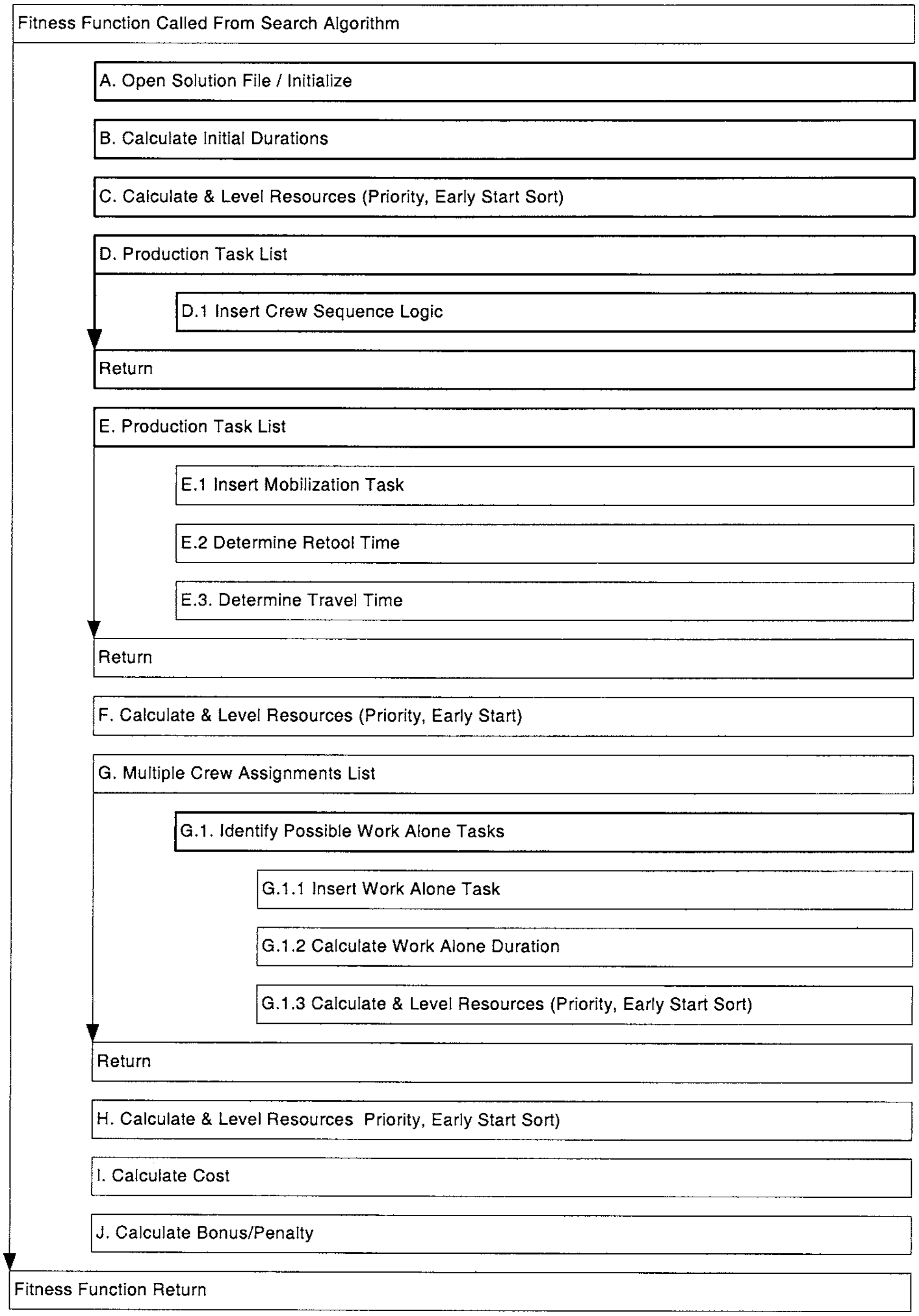


Fig. 7. FIRS fitness function algorithm

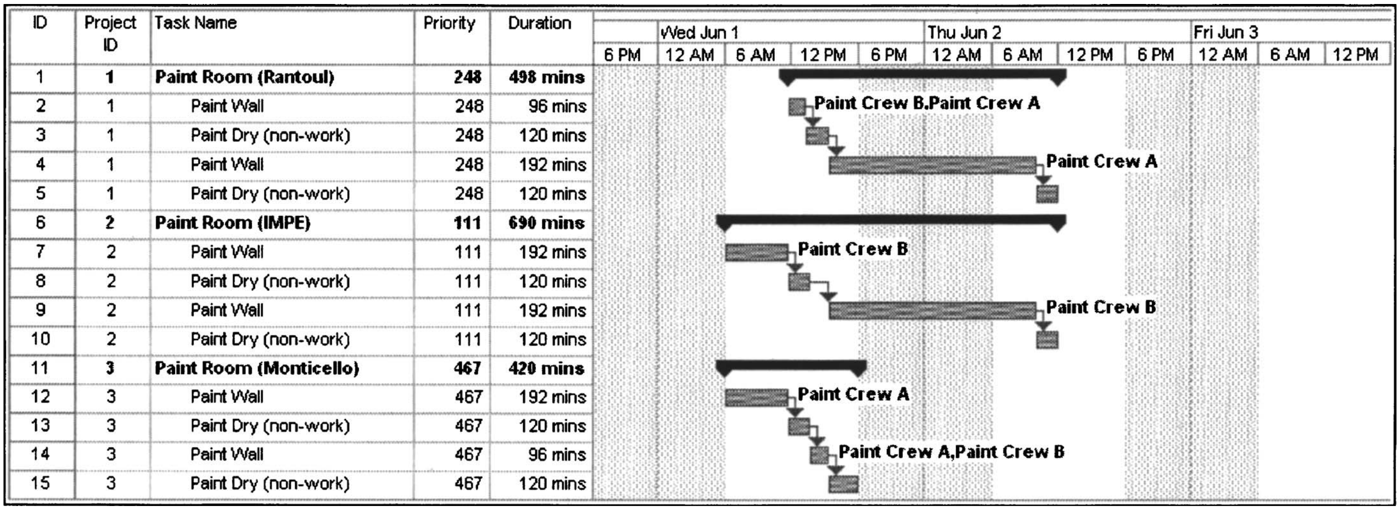
does not imply that the highest ranked project will be completed first. Priority leveling allows project activities to have access to assigned resources based on their priority. As a result, a lower priority project could be completed before a higher priority project if those projects did not share any resources.

In traditional construction scheduling, this is the end of the evaluation. If the primary concern is direct cost, then this direct cost would be provided to the project manager. For the facility/infrastructure domain, however, the direct cost is an insufficient measure to compare project plans. It is insufficient because facility/infrastructure projects are distributed over a geographical region. The cost of mobilizing to complete tasks across such a distribution—an indirect cost—could be greater than the direct cost of completing the actual construction production.

To determine where mobilization and travel are required, the FIRS algorithm adds disjunctive arcs (Han 1988) to link crew flows across projects. Once the crew sequence between projects has been added to the schedule, the time required to travel between activities is calculated. The travel task is added to the project to which the crew is moving. If the type of work being accomplished is different from the type of work the crew will be performing, then a trip to the closest depot is added as mobilization duration.

At this point, the inclusion of activities with crew assignments

J. Constr. Eng. Manage., 2006, 132(12): 1294-1305



ID	Project ID	Task Name	Priority	Duration
1	1	**Paint Room (Rantoul)**	248	498 mins
2	1	Paint Wall	248	96 mins
3	1	Paint Dry (non-work)	248	120 mins
4	1	Paint Wall	248	192 mins
5	1	Paint Dry (non-work)	248	120 mins
6	2	**Paint Room (IMPE)**	111	690 mins
7	2	Paint Wall	111	192 mins
8	2	Paint Dry (non-work)	111	120 mins
9	2	Paint Wall	111	192 mins
10	2	Paint Dry (non-work)	111	120 mins
11	3	**Paint Room (Monticello)**	467	420 mins
12	3	Paint Wall	467	192 mins
13	3	Paint Dry (non-work)	467	120 mins
14	3	Paint Wall	467	96 mins
15	3	Paint Dry (non-work)	467	120 mins

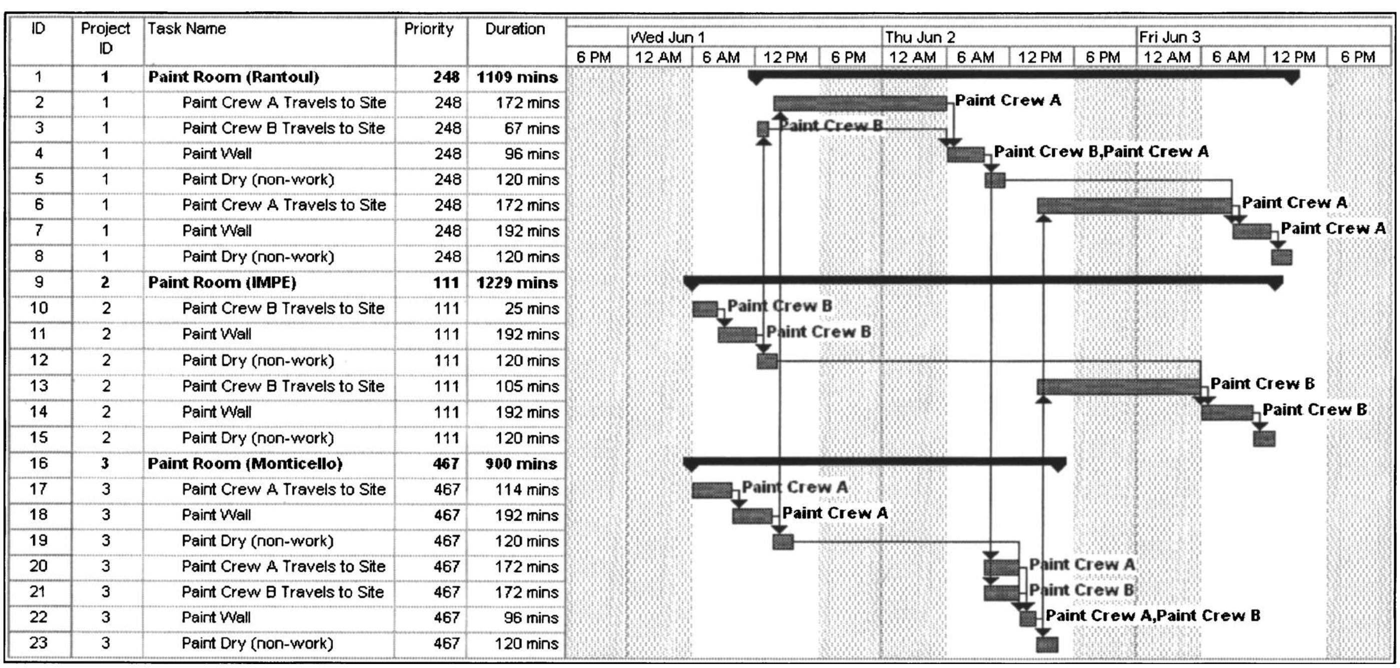
Fig. 8. Default duration and leveling complete

may have resulted in an overallocation of crews; the schedule is leveled again, as shown in Fig. 7, Steps E and F. The sequence of crew flows is maintained, because the crew flow sequence is now included in the schedule as logical links between individually assigned crew mobilization activities. Fig. 9 shows the schedule from the example project with crew sequence added and releveled.

For activities with multiple crews, it is likely that crews will not arrive simultaneously. If there are no physical constraints, crews arriving early should be able to begin upon arrival. Processing this condition is shown in Fig. 7, Step G. Following the inclusion of each of these "work alone" or "staging" tasks, the schedule is recalculated. For example, Fig. 9, Activity ID 4 is to be accomplished by both Paint Crew A and Paint Crew B. Since Paint Crew B arrives at the site early, they should begin working. Fig. 10 illustrates a new activity inserted to show Paint Crew B starting upon arrival. Direct, indirect, and penalty (or bonus) costs are determined, and the cost of the project plan is reported back to the FIRS search algorithm in Steps I and J of Fig. 7.

Verification and Validation

Verification and validation represent two distinct steps. The verification check to see if the algorithm is functioning as designed. Validation checks to see if the expected result is meaningful. To achieve these two goals, FIRS modeling and algorithm went through a series of verification and validation tests. The verification tests were performed to ensure that the algorithm performs correctly, as designed. Three approaches were used: (1) The trace files which record intermediate results during the execution, (2)



ID	Project ID	Task Name	Priority	Duration
1	1	**Paint Room (Rantoul)**	248	1109 mins
2	1	Paint Crew A Travels to Site	248	172 mins
3	1	Paint Crew B Travels to Site	248	67 mins
4	1	Paint Wall	248	96 mins
5	1	Paint Dry (non-work)	248	120 mins
6	1	Paint Crew A Travels to Site	248	172 mins
7	1	Paint Wall	248	192 mins
8	1	Paint Dry (non-work)	248	120 mins
9	2	**Paint Room (IMPE)**	111	1229 mins
10	2	Paint Crew B Travels to Site	111	25 mins
11	2	Paint Wall	111	192 mins
12	2	Paint Dry (non-work)	111	120 mins
13	2	Paint Crew B Travels to Site	111	105 mins
14	2	Paint Wall	111	192 mins
15	2	Paint Dry (non-work)	111	120 mins
16	3	**Paint Room (Monticello)**	467	900 mins
17	3	Paint Crew A Travels to Site	467	114 mins
18	3	Paint Wall	467	192 mins
19	3	Paint Dry (non-work)	467	120 mins
20	3	Paint Crew A Travels to Site	467	172 mins
21	3	Paint Crew B Travels to Site	467	172 mins
22	3	Paint Wall	467	96 mins
23	3	Paint Dry (non-work)	467	120 mins

Fig. 9. Crew mobilization activities included

J. Constr. Eng. Manage., 2006, 132(12): 1294-1305

ID	Project ID	Task Name	Priority	Duration
1	1	**Paint Room (Rantoul)**	**248**	**993 mins**
2	1	Paint Crew A Travels to Site	248	172 mins
3	1	Paint Crew B Travels to Site	248	67 mins
4	1	Paint Wall (Starts Early)	248	192 mins
5	1	Paint Wall	248	10 mins
6	1	Paint Dry (non-work)	248	120 mins
7	1	Paint Crew A Travels to Site	248	172 mins
8	1	Paint Wall	248	192 mins
9	1	Paint Dry (non-work)	248	120 mins
10	2	**Paint Room (IMPE)**	**111**	**1143 mins**
11	2	Paint Crew B Travels to Site	111	25 mins
12	2	Paint Wall	111	192 mins
13	2	Paint Dry (non-work)	111	120 mins
14	2	Paint Crew B Travels to Site	111	105 mins
15	2	Paint Wall	111	192 mins
16	2	Paint Dry (non-work)	111	120 mins
17	3	**Paint Room (Monticello)**	**467**	**876 mins**
18	3	Paint Crew A Travels to Site	467	114 mins
19	3	Paint Wall	467	192 mins
20	3	Paint Dry (non-work)	467	120 mins
21	3	Paint Crew A Travels to Site	467	172 mins
22	3	Paint Crew B Travels to Site	467	172 mins
23	3	Paint Wall	467	96 mins
24	3	Paint Dry (non-work)	467	120 mins

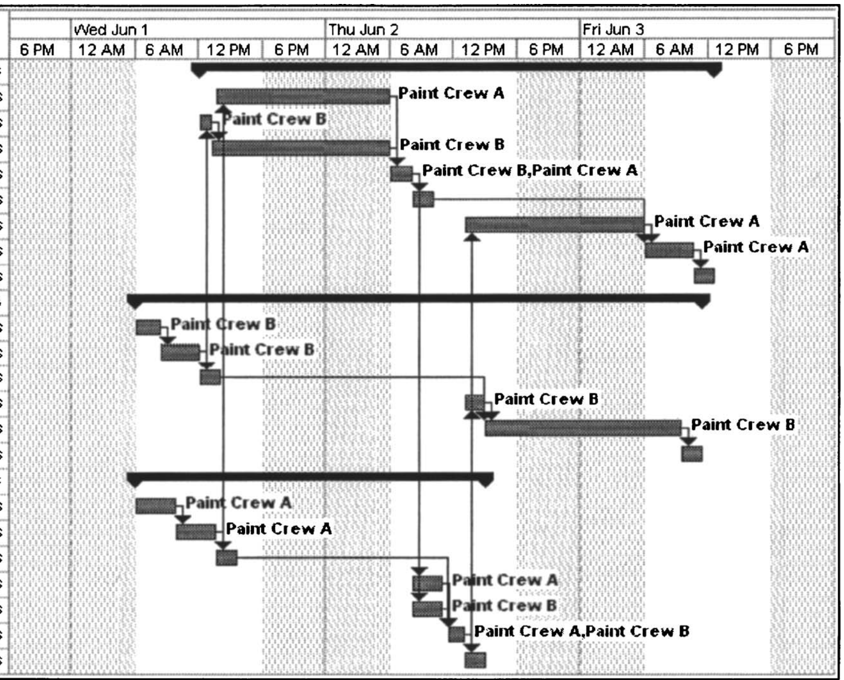


Fig. 10. New activity 4, resolving staging activities

solution sets which capture and compare known solutions with intermediate results at various steps, and (3) repeatable results which reset the random number generator within the genetic algorithm to make sure that identical results are obtained if the same random number seeds are used. These three methods are commonly used to verify evolutionary algorithms, such as FIRS. FIRS successfully passed these three tests. Further details of the verification tests performed on FIRS can be found in a publication by East (2005).

Validation tests involve confirmation tests to make sure that the proposed algorithm meets the facility manager's planning needs. Another attempt was made to use commercially available software to perform detailed resource scheduling tasks. A statistical evaluation of the results from the FIRS algorithm was compared to multiproject scheduling heuristics that were found in commercial software systems. A survey of facility management software vendors identified only a single vendor who provided any support for resource scheduling. A total of 24 test sets from various methods, including FIRS, were evaluated with a total of 960 data points. This comparison produced a statistically significant difference based on ANOVA (analysis of variance) (East 2005). Two interesting results were obtained from these statistical results. First, in all cases where projects were widely distributed, the FIRS algorithm provided solutions with statically significant lower cost. Second, problems with small distributed sets of projects showed a very high percentage of indirect cost, indicating that the crews were wasting a large portion of their time on nonproductive work, such as mobilization and travel. With these two results, the usefulness of the FIRS algorithm, and its importance, were validated.

Two additional validation steps were taken to determine the acceptability of FIRS results. First, a review of the requirements—identified by current or former facility managers interviewed during the course of this research—demonstrated that if timely solutions could be provided, the results would be used by facility managers. Second, the ability of the algorithm to assist in strategic planning was evaluated. In this series of experiments, alternative depot and work rules were simulated to identify lower cost solutions. Further details of the validation on FIRS algorithm can be found in work by East (2005).

Although the sample activities used in verifying and validating the algorithm, as shown in the previous section, seem to target the planning frequency of daily tasks, the proposed algorithm can support replanning in a dynamic environment, as frequently as the state of information changes. One of the strengths of the GA-based algorithms is that the same algorithm can produce good results fairly quickly, and the results improve evolutionally if more time is allowed. This advantage provides decision makers with the flexibility of being responsive when a quick decision is needed, and being comprehensive when accuracy is more critical.

The writers wish to note that current version of FIRS was designed for proof-of-concept and algorithmic transparency, so that each step in the algorithm could be easily traced and verified. We do expect future versions of FIRS to be implemented in C or C++ programming languages, rather than the current Visual Basic and Microsoft Project, for both efficiency and speed.

Future Research

The writers believe that GA-based resource planning algorithms, such as FIRS, are particularly suitable for planning and managing emergency responses—during and after disasters—where resources are scarce and the results are critical. The proposed FIRS concept to manage multiple projects can be extended to streamline chaotic activities during emergency response. We also envision and are exploring the integration of the FIRS algorithm with real-time tracking technologies, such as global positioning system, radio-frequency identification, and wireless computing. This integration will enable real-time or near-real-time activity status for the project managers to dynamically plan and control their

J. Constr. Eng. Manage., 2006, 132(12): 1294-1305

projects and resources. As a result, project managers can: (1) accomplish more work for the same budget, (2) more quickly respond to emergencies, and (3) evaluate the impact of strategic decisions (East 2005).

Conclusions

Previous research, related to resource allocation problems, covers areas that pertain to exact solutions of small theoretical problems or simple heuristic approaches to individual construction schedules. The research described in this paper breaks new ground in the evaluation of resource allocation decision-making in the context of multiproject domains. FIRS provides an effective tool for modeling multiproject resource domains, such as those encountered by facility and infrastructure managers. Three factors lead to this conclusion. First, FIRS was shown to reduce indirect project costs, when compared with standard heuristics. FIRS results were statistically significant for project sets whose projects were distributed through a geographic space. Second, FIRS explicitly models issues identified as important for facility management tasks. Thus, the approach taken by FIRS may be easily understood and adopted by project managers. Finally, FIRS may be used to view the effects of alternative staffing and deployment decisions on the facility management budget.

The discovery of a formalized notion of "Work Rules" is the most significant contribution of this research. The explicit modeling of Work Rules frees the project manager from needing to make explicit choices about crew assignments, because Work Rules allow the automated linking of alternative crew assignments to appropriate activities. Moving the focus of project management activities away from explicit resource allocation decisions allows project managers and shop foremen to concentrate on decisions for which each is actually responsible. Project managers and their staff are able to spend their energies prioritizing projects. Shop foremen may spend their time identifying Work Rules that are appropriate for the specific crews they have available and determining crew composition.

The next contribution of this research is the identification and modeling of the full cost associated with construction schedules. This research identifies the true mobilization costs of project priority and crew assignment decisions. Mobilization costs include both the cost of moving through the geographic space and the cost of restocking materials and equipment, as the type of work required changes over time. The model also allows the consideration of differential arrival times by explicitly calculating work accomplished by crews arriving early. The implementation of the domain model, as demonstrated by the FIRS program, provides a unique simulation environment for managers in several domains. FIRS allows the project manager to explore decisions of project priority and crew assignment. Beyond that, decisions regarding the quantity and application of crews, and the interaction of depots and work zones, may be fully explored. The significance of this simulation capability cannot be over-stated. A tool to evaluate indirect construction costs is of critical importance; in particular, to small construction business owners. While managers of such firms may be expert craftsmen, the management of "hidden" variable costs often limits the viability or growth of such firms. Using FIRS, small business managers can identify the results of crew allocation decisions, allowing the firms to grow beyond the level that can be managed by one individual.

While investigations using FIRS in this research considered only the indirect costs, the FIRS model and algorithm allows a complete representation of direct costs associated with crew and equipment productivity. As a result, FIRS has the capability to simultaneously search for the lowest combination of direct and indirect costs to complete a given set of projects. The final major contribution of this research was the creation of a multiattribute hybrid-GA/heuristic search tool. This tool demonstrates how searches may be accomplished across multiple simultaneous variables, governed by user-driven heuristics. Such an approach provides a rich environment in which to investigate a variety of problems in many domains. This environment may be further extended by considering input variables as decision variables in a broader problem statement.

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