MULTI-OBJECTIVE OPTIMIZATION FOR THE
CONSTRUCTION OF LARGE-SCALE
INFRASTRUCTURE SYSTEMS

By Amr Kandil and Khaled El-Rayes

ABSTRACT
This paper presents the development of an advanced Information Technology Framework for Optimizing Construction Utilization of Resources in Civil Infrastructure Systems, named IT-FOCUS. The main objectives of this framework are to: (1) develop robust optimization models for minimizing construction cost, and duration, while maximizing quality; and (2) formulate scalable methodologies for solving large-scale construction optimization problems. To this end, the present framework is implemented using an advanced multi-objective genetic algorithm that is capable of generating optimal trade-offs between construction cost, duration, and quality. To enable the optimization of large-scale infrastructure projects, the algorithm is parallelized using the manager-worker paradigm of parallel and distributed computing. The parallel implementation of the algorithm utilizes the message passing interface (MPI) standard to distribute genetic algorithm computations over a cluster of 50 Intel Xeon processors. A number of large-scale construction projects with sizes ranging from 180 to 720 activities were evaluated using the 50 processor cluster to evaluate the computational requirements for optimizing real-life construction projects. The results of this evaluation highlight the significant computational savings that can be achieved by the implemented parallel computing framework.

KEY WORDS
Genetic algorithms, parallel computing, optimization, quality, cost, duration.

INTRODUCTION
The civil infrastructure systems in the United States are rapidly aging and deteriorating, including existing transportation systems, water and sewage networks, utilities and telecommunications facilities (ASCE 2002). To remedy this urgent problem, public expenditures on infrastructure systems have increased in recent years. For example, total expenditures in fiscal year 2000 on highway capital outlay and maintenance projects alone reached a volume of $87 billion (FHWA 2000), and the Federal Highway Administration estimates that an average of $94 billion per year is needed over the next 20 years to improve the nation’s highways and bridges (USDOT 2000). Furthermore, the American Society of

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Civil Engineers (ASCE) estimates that $1.6 trillion of public investment are needed to revitalize the nation’s civil infrastructure systems over the next five years (ASCE 2002). To maximize long-term return on this public investment, government agencies have recently started utilizing new types of contracting methods that are designed to achieve multiple project objectives, including minimizing construction cost and duration, while maximizing its quality.

In recent years, many government agencies have started to apply new bidding and contracting methods, including: (1) bidding on cost/time (i.e. A+B method) to encourage competition among contractors to minimize project duration (Herbsman 1995, El-Rayes 2001); (2) incentive/disincentive contract clauses that provide financial incentives to reduce construction duration (Jaraiedi et al. 1995); (3) nighttime construction that seeks to cut service disruption and project time by requiring contractors to work during off-peak nighttime hours (Ellis and Amos 1996, El-Rayes and Hyari 2002); (4) warranty contracting that attempts to improve construction quality by making contractors liable for the performance of the facility after project completion (Anderson and Russell 2001, ENR 2002); and (5) multi-parameter contracts that provide incentives to contractors to improve quality performance (Anderson and Russell 2001).

The recent application of the aforementioned new and emerging contracts present decision-makers in the Architecture/Engineering/Construction (A/E/C) industry with new and serious challenges, including: (1) how to optimize the utilization of construction resources in order to satisfy multiple and conflicting contractual objectives; and (2) how to efficiently solve this multi-objective large-scale construction optimization problem. While many available models are capable of optimizing the utilization of construction resources, there has been little reported research to address these two main challenges. This paper presents the development of an advanced Information Technology Framework for Optimizing Construction Utilization of Resources in Civil Infrastructure Systems, named IT-FOCUS which is composed of a: (1) a multi-objective genetic algorithm module that is designed to support multi-objective decision-making in construction planning; and (2) a parallel computing module that is designed to enable the solution of large-scale construction optimization problems.

MULTI-OBJECTIVE GENETIC ALGORITHM MODULE

The purpose of this module is to formulate and implement an advanced multi-objective genetic algorithm that is capable of minimizing construction cost, and duration, while maximizing quality. This module is designed to transform the traditional 2-dimensional time-cost tradeoff analysis to an advanced 3-dimensional time-cost-quality tradeoff analysis. This transformation provides construction planners and decision makers in infrastructure systems with a much-needed model that is capable of: (1) generating optimal/near optimal resource utilization plans that optimizes construction time, cost and quality; (2) considering and quantifying quality in construction optimization; and (3) visualizing 3-dimensional representation of the trade-offs among project time, cost and quality in order to support decision-makers in evaluating the impact of various resource utilization plans on project performance. This module is developed in three main stages: formulation, quality
quantification and implementation. These three development stages are described in more
details in the following sections.

**FORMULATION STAGE**

The objective of this development stage is to formulate a robust multi-objective genetic
algorithm that supports the 3-dimensional time-cost-quality tradeoff analysis. To this end, the
genetic algorithm is designed to consider all relevant decision variables that may have an
impact on project time, cost or quality for each construction activity in the project. This
includes: (1) construction method \( (m) \), which indicates the availability of different types of
materials and/or methods that can be utilized; (2) crew formation \( (f) \), which represents
feasible sizes and configurations for construction crews; and (3) crew overtime policy \( (p) \),
which represents available overtime hours and nighttime shifts. In order to control the
complexity of the optimization model, the present model combines these three major
decision variables into single decision variable named resource utilization \( (n) \). As such, each
feasible solution for the entire project can be represented by a genetic algorithm string that
specifies the resource utilization option \( (n) \) for each activity \( (i = 1 \text{ to } I) \), and therefore this GA
string is designed to have a length equal to the number of activities in the project \( (I) \).

The present multi-objective genetic algorithm module is designed to enable the
minimization of construction time and cost, while maximizing its quality. The module is also
designed to quantify and measure the impact of various resource utilization decisions on
performance in each of the identified three project objectives in this stage of development.
To this end, the module incorporates three major objective functions as shown in the
following three equations to enable the evaluation of project performance in construction
time, cost, and quality, respectively.

Minimize Project Time = \( \sum_{i=1}^{I} T_{i}^{n} \)  \hspace{1cm} (1)

Where, \( T_{i}^{n} \) = duration of activity \( (i) \) on the critical path using resource utilization \( (n) \). In
this model, project duration is estimated using newly developed algorithms for the
scheduling of construction and renewal of highways (El-Rayes 2001, El-Rayes and Moselhi
2001).

Minimize Project Cost = \( \sum_{i=1}^{I} [ (M_{i}^{n} + D_{i}^{n} \times R_{i}^{n} ) + (B_{i}^{n}) ] \)  \hspace{1cm} (2)

Where, \( M_{i}^{n} \) = material cost of activity \( (i) \) using resource utilization \( (n) \); \( D_{i}^{n} \) = duration of
activity \( (i) \) using resource utilization \( (n) \); \( R_{i}^{n} \) = daily cost rate in $/day of resource utilization
\( (n) \) in activity \( (i) \); \( B_{i}^{n} \) = subcontractor lump sum cost for resource utilization \( (n) \) in activity \( i \),
if any.

Maximize Project Quality = \( \sum_{i=1}^{I} \sum_{k=1}^{K} \omega_{i,k} Q_{i,k}^{n} \)  \hspace{1cm} (3)

Where, \( Q_{i,k}^{n} \) = performance of quality indicator \( (k) \) in activity \( (i) \) using resource
utilization \( (n) \); \( \omega_{i,k} \) = weight of quality indicator \( (k) \) compared to other indicators in activity
(i); and \( w_t_i \) = weight of activity (i) compared to other activities in the project. In this model, an innovative and practical approach is utilized to measure and quantify construction quality using Equation (3).

**QUALITY QUANTIFICATION STAGE**

In order to facilitate the measurement and quantification of construction quality, the incorporated quality objective function (see Equation 3) enables the consideration of a number of measurable quality indicators for each activity in the project. These indicators have been investigated and identified in recent studies that were aimed at developing quality-based contractor pre-qualification systems (Minchin and Smith 2001, Anderson and Russell 2001). The identified quality indicators were derived from performance-based models that correlate the long term performance of the end product of each activity to its quality indicators. For example, Table 1 illustrates a sample of these quality indicators for the concrete paving activity that includes compressive strength, flexural strength, and ride quality.

Table 1: Construction Quality Indicators (Minchin and Smith 2001)

<table>
<thead>
<tr>
<th>Construction Activity</th>
<th>Possible Construction Quality Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Pavement</td>
<td>W/C Ratio, Consolidation/density, Air content, Thickness, Compressive Strength, Flexural Strength, Ride Quality</td>
</tr>
<tr>
<td>Bituminous Pavement</td>
<td>Compaction density, Asphalt content, Gradation, Surface smoothness, Thickness, Aggregate quality, Void ratio, Skid resistance</td>
</tr>
<tr>
<td>Bridge Deck</td>
<td>Consolidation/density, Rebar cover, W/C ratio, Density, Curing, Air content, Strength</td>
</tr>
<tr>
<td>Structural Concrete</td>
<td>Consolidation/density, Rebar cover, W/C ratio, Density, Curing, Air content, Strength</td>
</tr>
<tr>
<td>Base Course</td>
<td>Aggregate quality, Drainage, Gradation, Thickness, Compaction/density, Moisture content</td>
</tr>
<tr>
<td>Embankment</td>
<td>Compaction/density, Moisture content, Material quality, Uniformity, Drainage</td>
</tr>
</tbody>
</table>

Quality indicators should be selected in a way that allows practical and objective measurement of performance in each indicator as shown in Table 1. For example, performance in compressive strength and ride quality indicators can be easily tested and measured using a standard test for concrete compressive strength and pavement ride quality test, respectively (ASTM 2003a; ASTM 2003b). For each resource utilization option (n), the results of these quality performance tests can be easily obtained and stored in a similar way to existing methods that collect and analyze cost and time performances from previous projects. In fact many Departments of Transportation (DOTs) are currently gathering and storing this type of data from their ongoing projects using a variety of forms, such as the PCC Daily Paving Record (Form BC 2531) and the Resident Engineer’s Daily Report (Form CEM-4501) used by the Illinois DOT and CalTrans, respectively (IDOT 2002; Caltrans
This collected and stored data can be statistically analyzed in order to estimate the construction time, cost, and quality that can be expected from employing resource utilization (n) in activity (i) for the project being planned.

It should be noted that test results for the selected quality indicators are often expressed in different units of measurement. As such, they need to be transformed to a unified system of measurement that can be consistently used to evaluate performance in different quality indicators. In this model, the results of quality tests in different indicators are transformed to a common utility value that ranges from 0% to 100% (Meredith et al. 1985) in order to represent the degree of satisfaction of quality performance in each indicator.

The formulated quality objective function (Equation 3) enables the aggregation of the estimated quality for all the considered activities to provide an overall quality at the project level using a simple weighted approach, as shown in Figure 1. For each activity being evaluated for quality, this method requires planners to identify two types of weights: (1) weight of the activity (wt) to represent the importance and contribution of the quality of this activity to the overall quality of the project; and (2) weight of quality indicator k (wt,k) in activity i to indicate the relative importance of this indicator to others being used to measure the quality of the activity. These two types of weights are used to estimate the overall quality performance at the project level, as shown in Equation (3). The illustrated method in Figure 1 can be applied to additional construction activities using other measurable quality indicators similar to those suggested by Anderson and Russell (2001), and Minchin and Smith (2001), as shown in Table 1.

![Figure 1: Quantification of Construction Quality.](image)

### IMPLEMENTATION STAGE

This module is designed to perform the multi-objective genetic algorithm computations in three cyclic tasks: (1) genetic algorithm (GA) initialization to create an initial set of solutions that represents feasible resource utilization plans for constructing the project; (2) fitness evaluation to identify the construction time and cost for each of the generated resource
utilization plans; and (3) generation evolution to create a new generation of solutions using the selection, mutation, and crossover operations (El-Rayes and Kandil 2004; Goldberg 1989; Deb 2001; Deb et al. 2001). These three tasks are explained in more details in (El-Rayes and Kandil 2004) and are executed on a network of parallel processors in the present study to enable the optimization of large-scale projects.

PARALLEL COMPUTING MODULE

The main purpose of this module is to develop a robust parallel computing environment that is capable of transforming the optimization of large-scale construction planning problems from an intractable problem to a practical and feasible one. The design of the parallel computing module utilizes the manager/worker environment of parallel programming, which enables a manager processor to control (1) the distribution of computational tasks over worker processors; (2) the execution of programs on all utilized processors; and (3) the collection of results from all worker processors (Thiagarajan and Aravamuthan 2002). The communication among the manager and worker processors is implemented using a recently developed standard for developing parallel programs that run on Scalable Parallel Computers (SPCs) and/or networks of computer workstations called the message passing interface (MPI) (Snir et al. 1998). The main reason MPI was selected as a communication medium for the developed parallel computing environment is its wide acceptance as a standard for parallel programming in both academia and the industry, and its support for portability (Gropp et al. 1999). This makes the developed environment operable on a very large range of computing systems. The present parallel computing module is developed in two main stages: implementation and performance evaluation, which are described in more details in the following sections.

IMPLEMENTATION STAGE

The implementation of the parallel computing module was performed by first structuring the multi-objective GA framework for parallelization and then applying the MPI communication functions. The execution of the present environment consists of a number of independent processes that execute dissimilar code on separate processors. These processes communicate through calls to MPI communication primitives, and are arranged in a communicator, which houses grouping and communication context information of these processes (Gropp et al. 1999).

The two main MPI communication functions used in the development of the present module are the MPI_Scatter and the MPI_Gather functions. The MPI_Scatter function is used in the present environment for sending individuals from the manager processor to the worker processors as shown in Figure 2. The MPI_Gather function, on the other hand, is used to return fitness values of the evaluated individuals to the manager processor as shown in Figure 2.
PERFORMANCE EVALUATION STAGE

The performance of the present module was evaluated using the University of Illinois’s Turing Linux Cluster, which consists of 208 dual-processor machines (for a total of 416 processors) with two 1 GHz Pentium III processors and 1 GB of RAM each. The cluster was accessed through a 1.5 GHz quad-processor Pentium III Xeon front-end server. The primary network connecting the cluster machines is a high-bandwidth, low-latency Myrinet network. In addition, all machines in the cluster are also connected by a 100 Mbs switched, full-duplex Ethernet and there is a 1 Gbs link between the front-end and the primary switch (CSE 2003).

Different numbers of processors ranging from 1 to 50 were used for the performance evaluation tests, and the developed algorithm was tested using three sample construction project composed of 180, 360, and 720 activities respectively. As such, the performance of the present module was evaluated using 150 experiments that represented various combinations of project sizes and parallel processors. The performance metrics used in this performance evaluation stage includes the elapsed time and parallel speed-up measures of performance.

Elapsed Time

The elapsed time ($T_p$) is the time required by the parallel framework to perform the GA functions explained in and in Figure 2. Elapsed time is composed of two main components. The first is the evaluation time ($E_t$), which estimates the time required for function evaluation by processors. The second component of the elapsed time on the other hand is the total communication time ($C_t$). Elapsed time is given by equation 4 (Cantú-Paz 2000).

$$T_p = C_t + E_t = \alpha + \beta \times p + \frac{S \times T_{1}}{p}$$  \hspace{1cm} (4)
Where, \( S \) = number of individuals in the GA population; \( p \) = number of processors used; \( x \) = empirical factor associated with efficiency of the implementation; \( T_f \) = time required for the evaluation of a single individual; \( \alpha \) = communication time constant which depends on the number of individuals in the population and the size of GA string; \( \beta \) = slope of the communication function which depends on the number of individuals in the population and network latency.

The total elapsed time for the developed model was measured for each of the three tested project sizes using a varying number of parallel processors ranging from 1 to 50, as shown in Figure 3. The results of this analysis illustrate the significant computational time savings produced by the parallel computing frameworks, especially for large projects. For example, the total elapsed time for analyzing the 720 activity project was reduced from 360 hours using 1 processor to about 48 hours using 50 processors. This significant time reduction transforms the optimization of this example project from an impractical problem that requires approximately 15 days of continuous computing time on a single processor to a feasible problem that can be analyzed over a weekend on a network of unutilized office computers.

![Figure 3: Total Elapsed Time per Generation](image)

**Parallel Speed up**

The second measure of performance utilized in this model is the parallel speed up. This measure of effectiveness compares the performance of the parallel GA to that of a serial GA. The measure is a quotient of elapsed time of a serial GA and that of the parallel GA. Hence the speed up can be given by the following equation (Cantú-Paz 2000).

\[
\psi = \frac{T_s}{T_p}
\]  

(5)

Where, \( \psi \) = parallel speedup; \( T_s \) = elapsed time of the serial GA.

The parallel speedups of the developed framework were evaluated for the earlier described 150 experiments. A speed of 4 and 8 times the speed of the serial algorithm were achieved for the 180 and 720 activity projects, respectively. These obtained parallel speedups
clearly displayed Amdahl’s effect, which predicts that speedup would increase as the problem sizes increase (Quinn 2004).

SUMMARY

This paper presented the development of an advanced Information Technology Framework for Optimizing Construction Utilization of Resources in Civil Infrastructure Systems, named IT-FOCUS. This framework was developed in two main modules: (1) a multi-objective genetic algorithm module; and (2) a parallel computing module. First, the multi-objective genetic algorithm module was developed to support multi-objective decision-making for the construction and renewal of civil infrastructure systems. The module was designed to search for optimal resource utilization plans that minimize construction time and cost while maximizing its quality. As such, it provides the capability of transforming the traditional 2-dimensional time-cost tradeoff analysis to an advanced 3-dimensional time-cost-quality tradeoff analysis. Second, the parallel computing module is developed to support the optimization of construction planning in large-scale projects. The module was implemented to support the parallelization of genetic algorithm computations over a network of processors. The performance of the module was evaluated using 150 experiments that represented various combinations of project sizes and parallel processors. In each experiment, the performance of the framework was analyzed using two metrics: elapsed time, and parallel speed-up. The results of this analysis highlight the robustness of the developed module and illustrate its capabilities of providing improved efficiency in optimizing large-scale construction planning problems with accelerated processing speed reaching up to 8 times faster than that achieved on a single processor. The new capabilities provided by IT-FOCUS provide much-needed support for construction planners and enable them to efficiently and effectively perform multi-objective optimization for large-scale construction optimization problems that were previously considered impractical due to their extensive computational time requirements. To further enhance the practicality of IT-FOCUS, future research work will focus on transforming the platform of the parallel computing module from a cluster of processors on a supercomputer to a network of personal computers that is available to most engineering organizations.

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