Logistics of Earthmoving Operations

Simulation and Optimization

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Licentiate Thesis in Transport Science
With specialization in Transport Systems
June 2013

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Akademisk avhandling som med tillstånd av Kungliga Tekniska Högskolan i Stockholm framlägges till offentlig granskning för avläggande av teknologie licentiatexamen fredagen den 14 juni 2013 kl. 14.00 i sal V2, Teknikringen 76, Kungliga Tekniska Högskolan, Stockholm.

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Abstract

Earthworks are a fundamental part of heavy construction engineering and involve the moving and processing of the soil surface of earth. Normally, earthmoving operations are carried out during the early stages of heavy construction projects. To a large extent, the success of the fundamental earthmoving determines the sequence of the remaining parts of a project. Furthermore, the operations require expensive heavy equipment as well as manpower. Thus, improving the efficiency of earthmoving operations is a primary target from the point of view of the project management.

This thesis develops simulation and optimization methods for logistics of earthmoving operations. Modeling earthmoving operations correctly is essential to ensure the credibility of simulation, and the well-known CYCLONE modeling methodology is employed to represent the earthmoving logistics. Discrete event simulation techniques are used to capture the interaction between resources and the randomness of the earthmoving activities. A prototype has been developed (Paper I) to demonstrate that the capability of the simulation system of evaluating alternative operating strategies and resource utilizations for earthmoving operations at a detailed level, as well as conducting productivity estimation and Total Cost of Ownership (TCO) calculations. The simulation system is then integrated with optimization to solve the optimal fleet selection problem for earthmoving operations (Paper II and III). Two optimization objectives are formulated and solved using the proposed simulation-based optimization framework and a genetic optimization algorithm: TCO minimization and maximization of productivity. The case studies show that the proposed mechanism can effectively allocate an optimal equipment combination for earthmoving operations and hence serve as an efficient tool for construction management. The main aim of the integrated simulation-based optimization platform is to act as a sales tool to help customers optimize their fleet and eventually their sites.

In addition to the simulation-based optimization framework for earthmoving logistics, the thesis examines the possibility of reducing fuel consumption for articulated haulers which are the most fuel consuming machines in earthmoving (Paper IV). Fuel consumption has become one of the main focuses for automobile manufacturers and several studies have been carried out over the last years to evaluate the possibility of using topographical information and positioning systems to aid look-ahead control systems for road vehicles. Based on the assumption of available road slope information and positioning system, an optimal control problem is formulated to determine the optimal gear shift sequence and time of shifting. Model Predictive Control algorithms together with Dynamic Programming techniques are employed to solve the optimal gear shifting problem. Computer simulations show that both fuel consumption and travel time can be reduced simultaneously. In addition, the optimal gear shift sequence resembles the behavior of an experienced driver.
Acknowledgement

This licentiate thesis is a summary of my studies carried out at the Division of Traffic and Logistics at KTH. First, I owe my deepest gratitude to my main supervisor, Prof. Haris Koutsopoulos. Your wide knowledge, encouraging attitude and great enthusiasm have guided me through the project in a superb fashion. I would also like to thank Prof. Lars-Göran Mattsson for your valuable comments and suggestions to my work, and proofreading my thesis. Dr. Erik Jenelius joined the project team as my assistant supervisor last year. I wish to thank you for your unselfish support, care, and most of all, your friendship.

I would like to express my gratitude to our industrial partner Volvo Construction Equipment and the members of the project team, Erik Uhlin, Anders Westlund, Conny Carlqvist, Uwe Müller, who helped to establish a mutual trust and understanding between the industrial partner and the research team. Also to Jonas Larsson, Anders Fröberg, Gianantonio Bortolin, Reno Filla, Bobbie Frank, for your support, feedbacks and inspirational discussions.

The financial support from the Swedish Governmental Agency for Innovation System (Vinnova) is gratefully acknowledged.

I wish to thank my colleagues at the Division of Traffic and Logistics at KTH for the supporting company the past two years.

Finally, I wish to thank my friends and family for being a constant support.

Stockholm, June 2013

Jiali Fu
List of Papers


3. Fu J., Jenelius E., Optimal Fleet Selection for Earthmoving Operations, the 7th International Structural Engineering and Construction Conference (accepted), 2013.

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1. Introduction

1.1 Background

Heavy construction is one of the largest industries in civil engineering; common examples include the construction of highways, roads, dams, airports, commercial buildings and industrial plants, and industries such as mining and quarries etc.

Construction projects in general are complex, and heavy construction projects in particular are large in scope. Earthworks are a fundamental part of construction engineering and involve the moving and processing of the soil surface of earth. Normally, earthworks are carried out during the early stages of heavy construction projects. To a large extent, the success of the fundamental earthworks determines the sequence of the remaining parts of a project.

Most construction projects have a completion date specified in the contract, which determines the planned duration of the project. If the project is not completed in time, damages may occur due to the unavailability of the facility. Moreover, in most cases construction contractors are obliged to pay a penalty for every day of delay after the stated completion date. Much of earthworks involve the replacement or reform of large quantities of soil and the operations require specially designed heavy equipment with significant purchasing/leasing price, as well as high operating and maintenance costs. Apart from the substantial investment together with high operating cost, the expenditure on manpower is also considerable due to reasons like rough working conditions, the training process of the equipment operators etc. As the competition in the construction branch is getting harder, it is thus necessary for the project management to estimate and plan the operations as accurately as possible.

The project management team is often challenged to make “the right decisions” at the strategic and tactical level both before and throughout a construction project. At the strategic planning stage, the long-term decisions are made with the entire project as the target; at the tactical level, the management focuses on short-term operating issues and resolution of issues that come up due to uncertainty of the operating environment. Both strategic and tactical productivity estimation is indispensable for planning and operating purposes. However, there are a number of difficulties to overcome in the planning process due to the characteristics of construction operations:

1. Each construction project possesses unique characteristics and hence requires tailor-made planning at the strategic and operational levels simultaneously.
2. Construction operations are complex systems where many resources (equipment and manpower) collaborate to carry out tasks.
3. The operations are often impacted by uncertainties.
4. The dynamic nature of construction projects and the frequently re-configured environment at the construction sites make the planning process more demanding.
1.2 Problem Statement

The project described in this thesis is a collaboration between KTH Royal Institute of Technology in Stockholm and Volvo Construction Equipment (Volvo CE) in Eskilstuna, Sweden. Volvo CE was founded in 1832 in Sweden and is one of the oldest companies in the world still active in construction equipment. Today, Volvo CE is part of the Volvo Group, and develops and produces a wide range of 170 different types of construction machines that are used in various applications. Examples of the equipment manufactured by Volvo CE are wheel loaders, excavators, articulated haulers, motor graders etc.

Traditionally, the construction machines are developed, sold and supported as separate products. The main effort at Volvo CE today is focused on designing the machines at the early product development phase to reach an optimal operating condition at an individual level. A simulation tool named Site Simulation (Site simulation tutorials) is employed by the sales personnel today to recommend to customers a suitable set of machines and their configuration for relatively simple earthworks. However, this software does not adequately catch up with the rapid product development at Volvo CE. Moreover, the applicability of the Site Simulation is limited and it is not possible to assist the customers when the site operations grow large and complex. For studying the performance as an entire equipment fleet for complex construction operations, there is not yet a proper tool.

Being one of the market leading manufacturers of construction equipment, Volvo CE wants to offer complete solutions for heavy construction operations when they encounter customers with large construction sites and complex transport logistics. The customers’ sites normally differ in terms of layout, operational method, type of material handled etc. The different site operations will be evaluated in terms of Total Cost of Ownership (TCO) and environmental aspects. In construction business, the environmental impact is dominated by fuel consumption, which has become increasingly important in recent years with the fast rising fuel price and environmental focus among customers. The solutions should include the following features:

- Able to model construction site operations in a simple and easy-to-understand manner. Since the target users will be sales personnel, construction managers and development engineers, it is therefore not suitable to employ a modeling methodology which requires the diverse user group to possess a strong knowledge in a specific area or to spend many days of training to learn the modeling techniques.
- Able to model complex construction operations and increased accuracy of productivity estimation of site operations. Compared to the existing simulation software Site Simulation at Volvo CE, the new solution should be able to model complex construction logistics as well as to provide a more accurate productivity estimate of the construction operations.
- Catch the dynamic aspect of construction site operations and the interaction between the resources. As mentioned before, the site operations are highly dynamic and many resources collaborate to carry out tasks. Thus, the proposed modeling should be able to
reflect the dynamic character of site operations and the interdependent relations between resources.

- Able to perform optimization for a particular site operation. The optimization will be employed as the means for the sales personnel to help the customers designing the site layout, choosing operating methods, selecting an optimal fleet configuration etc. in terms of TCO and environmental aspects.
- Further examine the possibility of reducing fuel consumption for the construction equipment. Construction equipment is very fuel-consuming machinery because of its large mass and its heavy load of construction materials. Fuel cost of equipment has become a substantial part of the production cost in recent years due to the scarcity of fossil resources and stricter environmental policies. Although the development engineers working constantly to optimize the design of the machines with regard to their overall performance and fuel usage, improvement could still be made with the help of modern technologies such as site topographical information, intelligent transport system (ITS), etc. This improvement could be further incorporated into the optimization of the site operations.

### 1.3 Objectives

The overall objectives of the thesis are to develop a simulation method for modeling of earthmoving logistics, and to formulate and solve optimization problems for earthmoving operations in terms of Total Cost of Ownership and environmental aspects.

The simulation is designed to model the logistics of earthmoving operations and capture the interactions between different equipment at an arbitrary construction site. The efficiency of each earthmoving solution is evaluated through simulation in terms of TCO, productivity, fuel consumption, resource utilization, etc. For existing and future customers, the efficient design of site layout and machine configuration is the most important factors in reaching low production cost. The simulation model will facilitate the evaluation of real-world earthmoving operations and give the customers and sales personnel a better understanding of the dynamic behavior of the process. The result from the simulation will be utilized in an optimization algorithm to select the best possible fleet in the terms of TCO and productivity subject to the physical constraints.

The main aim of the project is to create a simulation-based optimization framework to act as a sales tool to help the customers optimize their fleet and eventually their sites. In addition, from the product development point of view this framework ensures that the right products are developed in the early development process.

A more specific objective is the further examination of reducing fuel consumption for articulated haulers, which are the most fuel consuming vehicles in earthmoving operations. Over the last years, several studies have been carried out to evaluate the possibility of using topographical information together with positioning system to aid look-ahead control systems for vehicles. However, these methods have not yet been investigated on off-road construction vehicles due to unavailability of three-dimensional (3D) information of the operating
environment. Based on the assumption of available road slope information and the vehicle’s location obtained from a positioning system, an optimal control problem is formulated to determine the optimal gear shift sequence and time of shifting. Optimality is here considered in the sense of both fuel consumption and travel time.

The simulation model of earthmoving operations is presented in Paper I. Paper II and III describe the optimal fleet selection problem for earthmoving operations in terms of TCO and productivity. Paper IV presents a gear shift optimization problem given that the road slope information and vehicle location are known.

1.4 Limitations

One of the limitations of the thesis it is that it only concerns the earthmoving operations, which is described in Chapter 2. Modeling and optimization of heavy construction operations in general are not covered here.

Another limitation concerning the implementation of the simulation and optimization framework for earthmoving operations developed in this thesis. At this stage, the work carried out is to examine the possibility of improving earthmoving operations and the software development of this framework is not considered here.

For the fuel consumption reduction problem of construction equipment, the assumption of available road topographical information is taken in the thesis. Moreover, this study focus on articulated haulers and the possibility for other heavy construction equipment is not yet investigated.

1.5 Thesis Outline

This licentiate thesis consists of five chapters. Chapter 1 presented an introduction to this licentiate thesis. The earthmoving operations and the commonly employed equipment are briefly described in Chapter 2. A literature review of the state-of-the-art research in construction engineering is given in Chapter 3 on a methodology basis. Chapter 4 includes a summary of the articles presented in scientific publications for the work described in this thesis. The final chapter, Chapter 5, concludes the thesis, discusses the usefulness of the proposed methods and gives an outlook into the future. The published articles are appended in the end of the thesis.
2. Earthmoving Operations

Earthworks, in their simplest form, involve processes such as excavating, hauling, dumping, crushing and compacting (Ricketts, Loftin and Merritt 2003). An earthmoving operation consists of the preparation of material, the loader/truck loading cycle, haulage of trucks to the disposal place, the deposition of the material and the trucks’ return trip to the loading station to start another load-and-haul cycle. The most common method in earthmoving is to employ a number of excavators, wheel loaders and haulers to prepare, excavate, load and transport soil. This method is more beneficial when the hauling distances and material quantities involved are relatively large. The second method is to use more independent equipment such as scrapers and wheel loaders to carry out the entire process, and this method is more appropriate when the transport distance is short. Depending on the scope and working condition of each project, different operation methods and machine types should be selected to maximize the overall performance of the operation.

2.1 Earthmoving Equipment

Earthwork operations are highly equipment-driven processes and the equipment costs constitute a major part of the investment and operating cost. In general, the most frequently employed equipment for earthworks are dozers, scrapers, wheel loaders, excavators, haul trucks and compactors.

*Dozers* are equipment with a metal blade installed at the front end of the vehicle, and are aimed for pushing excavated earth or other materials in earthworks. *Scrapers* are a type of “all-in-one” machinery specially designed for short distance earthmoving purpose as they are capable of excavating, hauling and placing soil independently. However, it is not economic to only employ scrapers performing earthmoving with long hauling distance and large quantities of soil. *Compactors* are equipment used for reducing the size of soil and other material.

*Wheel loaders* are machinery used for loading excavated material and have a bucket connected to its end for filling and emptying material. Loaders are also capable of moving larger pieces of earth to other places so they are not in the way of other equipment on site. Figure 2-1 shows a wheel loader produced by Volvo CE. However, loaders are not suitable for digging purposes since the bucket is not designed for deeper digging than the level of a vehicle’s wheels. The bucket is normally a removable attachment to the loader, and can be replaced with other devices for various purposes in construction operations.

*Excavators* are construction machines originally designed for excavating earth and loading it on haul trucks. An example of Volvo CE’s excavators is shown in Figure 2-2. The bucket is connected to the vehicle’s cabin by a two-part articulated arm. The section of the arm connected to the vehicle is the boom and the section that carries the bucket is called the dipper or dipper-stick. The cabin is sitting on a rotating platform with a tracked undercarriage. The track offers the vehicle a better mobility over rough terrains and the rotating platform gives a broad working angle for the arm. Additionally, the articulated arm allows the bucket to move
in different directions. Excavators in general are very flexible machinery not only for earthworks, but also various tasks in construction operations. With different attachments like breaker, grapple and auger, an excavator can be used for many other purposes in earthworks such as breaking material into smaller pieces, lifting or dragging, and drilling.

![Figure 2-1 A wheel loader manufactured by Volvo CE.](image1)

Rigid haulers and articulated haulers are the most common haul trucks for earthwork purposes, and are designed as off-road trucks since their size and total load are larger than...
what is permitted on public highways. Unlike rigid haulers, articulated haulers are vehicles used to transport large volumes of material on rough terrains. The machine is composed of two basic units; the front unit is the tractor section and the back unit is called the hauler or trailer section. In contrast to a rigid hauler or normal dump trucks, the tractor and trailer sections are attached together through an oscillating system which allows the two units to rotate about the vehicle’s waist. The strength of an articulated hauler is due to the rotating hitch and the frame steering, enabling the tractor and trailer to move independently of each other. Where rigid haulers have to take a longer path around an obstacle or risk getting stuck, the articulated haulers operate smoothly and safely, taking the shortest route between loading and dumping stations. Due to the maneuverability and accessibility in severe road environments, articulated haulers are usually employed in off-road operations, such as construction sites, landfill operations, earthmoving, mining, forestry etc. An articulated hauler manufactured by Volvo CE is displayed in Figure 2-3.

![Figure 2-3 An articulated hauler by Volvo CE.](image)

### 2.2 The Earthmoving Process

In an earthmoving process, a *preparation* step is needed if the material to be moved is not suitable for immediate loading.

*Loading* is the process of transporting earth from the prepared pile into trucks. Wheel loaders and excavators are the most employed machinery for loading. Depending on the material state and ground space limitations, one type of equipment may be more applicable than the other. In general, wheel loaders have larger bucket capacity but require a certain ground space to enable reversing and driving forward to scoop up material from the ground. They are more suitable for loading ready excavated and stockpiled material. In contrast, excavators have relatively small bucket volume but can load while remaining in the same position. Excavators are capable of material preparation since they can dig material from the untouched natural state, and can also separate large pieces of earth into smaller sizes. Excavators are normally placed on higher ground relative to the hauling units for easy loading purpose.
*Hauling* involves haul trucks traveling through roads with varying slopes and ground conditions as well as traffic intersections in order to transport earth to the deposit place. Depending on the final purpose of the operation, the earth is transferred from the trucks onto spreading piles or into crushers at the dumping station. Stationary or mobile crushers are equipped at the dumping station to transform the transported earth into smaller pieces. The crushed earth is essential material in civil engineering for construction of buildings such as houses, roads and bridges. The material is fed into the hopper which is connected at the top of the crusher. The hopper functions as a container to hold material to be crushed. Each crusher is designed to fragment material with a certain maximum size at a specific crushing rate, and the crushed material is then delivered to a screening machine which separates the material according to its size and transfers it for further processing. After depositing its load, the hauling units return to the loading station to start another load-and-haul cycle.

Figure 2-4 illustrates a typical earthmoving operation. Wheel loaders and articulated haulers are employed here for loading and transport.
2.3 Productivity Analysis and the TCO Concept

Productivity is a key aspect when evaluating the design of a process and it is the most commonly used performance measure in construction engineering. In an earthmoving operation, productivity is defined as the total output from the entire fleet, i.e. transported material in ton or m$^3$ per operating hour. However, only examining the productivity is insufficient for evaluating the performance of an operation. It is also important to use methods for total cost estimation at different levels of detail that are appropriate for the targeted applications. The concept of “Total Cost of Ownership” is frequently used in construction business for the direct and indirect costs of production. Conceptually, TCO is a management accounting term which evaluates the economic value of an investment. A TCO analysis includes total cost of acquisition, the operating cost as well as the productivity of a project, and gives the management a clear picture of the profitability over time. The common challenge of TCO analysis is however the collection of appropriate and accurate data.

The total cost $C_{tot}$ of TCO includes the capital cost $C_{cap}$ and operating cost $C_{opr}$ of equipment, where $C_{cap}$ covers the equipment’s purchasing price, residual value, depreciation, interest, insurance and taxes while $C_{opr}$ takes into account those costs which result from equipment operation and use. Normally, the operating cost contains operator cost, fuel consumption, spare parts, preventive maintenance and repair cost. The operating cost is subjected to the uncertainties of the operating environment. Production per hour $P$ is the output of a fleet of equipment working together (the total transported earth in this study), and is measured as weight (ton/h) or volume (m$^3$/h) per operating hour. Finally, TCO is defined as the cost per production unit and is obtained as the quotient between the total cost per hour and the production per hour.

Productivity and TCO are two conflicting aspects in an earthmoving operation. Naively minimizing the TCO may reduce the production rate and extend the time required to finish a target project. Other performance measures like the required production rate, the expected project duration and profitability should not be disregarded in the productivity and TCO analysis.
3. Literature Review

The prime function of construction management is to plan, procure, organize and control the activities of the projects and equipment resources (Edwards and Holt 2009). Regardless of its type, size and timetable, each project has to meet the conflicting objectives of time, cost and performance. The project management is thus challenged to balance the trade-off among the objectives both before and during a project. In the past decades, various techniques and tools have been developed to support the construction engineering in decision making.

In this section, a methodological review of the literature in construction management research is performed. The methodologies applied in this field can be divided into heuristic approaches, mathematical modeling, metaheuristic methods and simulation-based optimization approaches.

3.1 Heuristic Approaches

Construction engineering is traditionally an experience-based field and heuristic rules have dominated in the planning and management process. These heuristic methods generally provide good solutions, but do not always guarantee optimality of the solutions.

In a study reported in Mawdesley, Askew and Al-Jibouri (2004), four project planners were followed for a period of one week, revealing that much the planning processes of the managers were based on experience rather than careful analysis. The managers often made their decisions due to personal preferences and were not actually conscious of their choices. Depending on the chosen method for each operation, the preparation of selecting the right type and amount of equipment and the productivity estimation depended heavily on the planner’s skill and judgment. The construction methods employed were not only different from project to project, but also diverged among planners. The authors explained that the phenomenon is due to two reasons. First, each construction project is unique and it is impractical to apply a simple unified method to all. Also, the managers were very familiar with the planning problems so that they acted reflexively, and sometimes were unable to explain exactly what they were doing. Thus, the decision-making appeared to be subjective and highly relying on the individual planner’s intuition, knowledge and experience, while a formalized, systematic approach in construction planning was absent.

Most managers make decisions based on their years of field experience, judgment and rules of thumb in construction engineering rather than theory and analysis. For instance, Karshenas (1989) investigated the problem of choosing the optimal hauler truck capacity for various loader sizes in an earthmoving operation. Karshenas noted that the size of the loading unit is normally determined by the production required, and the matching truck for the selected loader is then chosen by calculating the unit production cost for different truck capacities or using some rules of thumb. The author came to the conclusion that the optimal truck capacity
for a loading unit is approximately 5 to 7 times the loader’s capacity. The detailed procedures of estimating the production of a loader-truck system can be found in the article.

In another study (Gransberg 1996) using the planners’ rules of thumb, the optimal number of hauling units \( N \) in an earthmoving operation at a quarry is determined as the quotient between the hauling unit’s cycle time \( T_{cycle} \) and its loading time \( T_{load} \), i.e.

\[
N = \frac{T_{cycle}}{T_{load}}.
\]  

(1.1)

The cycle time for a hauling unit contains the time for loading \( T_{load} \), traveling to the dumping station \( T_{haul} \) and returning \( T_{return} \), and the estimated delays \( T_{delay} \). However, \( N \) is normally not an integer number, and Gransberg pointed out that the maximum productivity of the entire system is ultimately controlled by the rounding-off decision of the number of hauling units. Two analytical methods on the rounding-off choice based on productivity and profit were demonstrated in Gransberg’s work.

Decisions in construction projects must be made quickly and efficiently, and most of the time the decisions are made on the job site. When a large number of workers and equipment are idle, the decision-maker is under much pressure to act promptly. Due to the lack of time to preform complicated calculations, the project managers may accept sub-optimal decisions. Based on the expert knowledge, researchers have made a number of attempts to develop computer-aided tools for assisting the managers in decision making.

For instance, Amirkhanian and Baker (1992) proposed a rule-based expert system with spreadsheet application to assisting the task of equipment selection in earthmoving projects. The system incorporated 930 rules collected from various experts working for earthwork contractors, equipment rental companies, equipment manufacturers’ sale representatives and several geotechnical engineers. Based on the information provided by the user, the computer system would recommend the most appropriate equipment for the specific operation using the collected rules. This system was also tested using the requirement for an actual project and the results indicated that the proposed system was consistent with the opinions of several human experts. The authors concluded that the knowledge acquisition, as well as the problems and solutions associated with it are the most important part of developing such an expert system. This study showed that the application of an expert system in earthwork equipment selection is feasible and it gave the users the accessibility to the expert knowledge.

Another knowledge-based expert system was proposed by Touran (1990) to help in selection of compactors for earthworks. This system was designed as a tutorial tool for inexperienced personnel, and took into consideration factors such as the degree of compaction, space constraints and size of the work site, soil type and properties, etc. The rule-based system made comparisons between suitable alternatives and selected the most economical equipment which gave the highest production rate.

In Eldin and Mayfield (2005), a spreadsheet application was developed to aid the selection of scrapers for large earthmoving operations. As mentioned before in Section 2.1, scrapers are
machinery capable of performing earthmoving operations independently. The knowledge-based system had eight integrated worksheets containing the database of scrapers, the performance charts taken from a manufacturer’s handbook, the cost data and soil properties etc., and provided a user interface to solicit all data entries to a project. Once the users entered the necessary information for a project, the system carried out nine calculation procedures outlined in the article and then selected the optimal fleet based on the minimum cost or maximum production rate which was defined by the user. The authors claimed that though the creation and data entry for this expert system were time demanding, it provided a common quantitative basis to the construction managers in evaluating different what-if scenarios on a more comprehensive level once the system is built.

Similar work that incorporated computer-based systems with expert knowledge in construction research can be found in Askew, et al. (2002), Mawdesley, Askew and Al-Jibouri (2004), Yang, et al. (2003). However, these heuristic methods are based on rules of thumb and engineering experience. The methods suffer from lack of mathematical validity and credibility and also do not guarantee optimal solutions. In addition, it is difficult to find the solutions efficiently using heuristic methods when the construction operations grow large and complex.

3.2 Mathematical Modeling

Numerous techniques using mathematical modeling have been established to provide productivity estimates and to optimize construction operations. The most frequently used methods are response surface methodology, queuing theory, fuzzy logic and rough sets.

Response surface methodology is one of the statistical methods designed to obtain an approximate functional relationship between the input factors and the output function (the response). The most employed methods to attain the relationship are regression analysis and artificial neural networks. Smith (1999) employed linear regression techniques to determine the impacts on productivity and bunch factor of the explanatory variables for earthmoving operations. The bunching in an earthmoving system is a situation in which haul trucks are gathered in groups and is mainly caused by the overcapacity of hauler trucks. Using data collected from 140 separate earthmoving operations, the regression model showed a strong linear relationship between operating conditions and productivity. The author concluded that the most significant factors for productivity estimation are the number of trucks, the bucket volume of the loading unit, and the truck travel time and distance. For the bunch factor however, the regression model gave poor results, and the author suggested using a nonlinear regression model or taking in more explanatory variables. An artificial neural network was applied in Schabowicz and Hola (2007) to predict productivity for earthmoving systems consisting of a certain number of excavators and haulers. Subsequently, Hola and Schabowicz (2010) presented another work which employs a neural network to determine execution time and cost of earthworks. The authors pointed out that the estimation of productivity might not be very accurate if only a single neural network is used, and for that reason the network was divided into subsets depending on the transport distance. A data set from an actual construction site in central Europe was used in the case study and the results showed that the
neural networks could accurately predict the productivity of different machine sets and earthwork conditions.

*Queuing theory* is a mathematical description of interdependent systems and is a frequently employed method in improving decision making and efficiency in operations research. The method has also been applied in research on construction processes from a systemic perspective. Based on the assumption of steady-state operation, Halpin and Riggs (1992) modeled an earthmoving operation with a single server (loader) and multiple customers (haulers). Both the inter-arrival time for the hauler trucks and the service time for the loader were assumed to be exponentially distributed which is a common assumption in queuing theory. However, the authors concluded that the assumption of steady-state operation was not justified since it normally takes a long period for an earthmoving system to reach such a state. The authors suggested introducing a transient phase of operation to solve this problem, but the solution of the modified model would be mathematically complex and hence lose the simplicity of queuing theory.

*Fuzzy logic* is a computational approach based on degree of trust rather than the standard logic of true or false. It allows elements to be partially in a set, and each element is given a degree of membership in a set dependent on its intensity of trust. Several researchers have applied this method in the studies of construction operations. Hanna and Lotfallah (1999) presented a fuzzy logic approach to select the most appropriate crane type in a construction project. The factors that affect the selection of cranes are divided into five different groups: site conditions, building design, economical condition, capacity of cranes, and safety issues. Additionally, each factor had a static or dynamic characteristic depending on if it was constant or not for a particular project. For each of the factors, the system translated the information about the suitability of crane types to the fuzzy sets or fuzzy if-then rules depending on the factor’s static or dynamic character. The resulting efficiencies were aggregated according to their importance weights, and the process could identify the optimal crane type with the highest overall efficiency. The authors remarked that this application was not only a way to eliminate the bias and prejudice of a project planner in the decision making process, but could also uncover any gap in the planner’s thinking.

In Cirovic and Plamenac (2006), three mathematical modeling procedures in the choice of construction machinery for operations at a concrete plant were proposed and compared. The three alternatives were a conventional model, a rough sets model and a fuzzy sets model. In the conventional model, the optimal choice of equipment was based on an economic analysis which computed the feasible output and cost of effective operating hour for each machine. *Rough set theory* is a mathematical method that synthesizes approximations of concepts in data sets which are obtained from measurements or human experts. The rough sets approach takes into consideration the data’s imprecision, uncertainty and incompleteness. Besides the cost of machines, the systems’ availability (e.g. whether an equipment is in order or in repair after failure) was also included in the rough sets approach. The third method used fuzzy set theory and considered parameters of production and conditions of production as the fuzzy variables. The authors noticed that the conventional method did not take account the interaction between machines and hence could not ensure the optimality of the recommended
choice. Meanwhile, the rough sets method and the fuzzy sets method gave more trustworthy solutions since they reflected the reality.

There are plenty of further examples in construction operations of employing mathematical methods and operations research techniques. For instance, Ulubeyli and Kazaz (2009) applied a multi-criteria decision-making approach in a selection problem of concrete pumps. Luu, et al. (2009) proposed a Bayesian belief network system to quantify the probability of delays in construction projects.

In general, modeling construction operations using mathematical methods is technically sound, but may appear too difficult or abstract to construction practitioners.

3.3 Metaheuristic Approaches

Metaheuristics is a set of computational algorithmic concepts which are grounded on biological and animal behavior and are normally used for solving combinatorial optimization problems. Metaheuristic methods are derivative-free and iteratively improve a candidate solution with respect to a measure of quality. Research in construction engineering using metaheuristic methods has been conducted in recent years. A detailed review of previous studies specially addressing metaheuristic methods was carried out by Liao, et al. (2011). The review showed that the methods frequently applied in this field are simulated annealing (SA), ant colony optimization (ACO), evolutionairy algorithms (EA), genetic algorithms (GA), particle swarm optimization (PSO) etc. Evolutionary algorithms/genetic algorithms are the most popular methods among all metaheuristic approaches. The authors listed a few reasons for their popularity. First of all, these methods are the earliest metaheuristic methods and have been accepted in the research field of civil engineering. Second, EAs and GAs can handle both continuous functions and combinatorial optimization problems. Last, these methods are not very computationally demanding and can normally find good solutions.

Simulated annealing (Kirkpatrick, Gelatt and Vecchi 1983) is an iterative procedure based on ideas from statistical mechanics, and the SA algorithm moves from a current solution to a neighborhood in search of optimality. The new solution is accepted if the objective function is improved; otherwise the solution is accepted with a certain probability. Son and Skibniewski (1999) presented a hybrid approach that combined a local minimizer with simulated annealing to solve the resource leveling problem. Resource leveling is a project management technique which reduces peak demand and minimizes day-to-day fluctuations of resource use. The objective in this study was to minimize the total deviation of resource requirement and a local optimizer using heuristic approaches was formulated to find the local optima in the first step. Subsequently, the simulated annealing model was employed to escape from the local optima and further improve the performance of the local optimizer.

The ant colony optimization algorithm takes inspiration from the social behavior of ants when they search for food from their nest (Dorigo, Maniezzo and Colorni 1996). The ants can always find a path from their nest to the food source, and leave a substance called pheromone on the ground to inform others about the most efficient trail. Other ants observe the pheromone and tend to follow the path. Eventually, trails with little pheromone will be
neglected and all ants join to the same path. Ng and Zhang (2009) presented an ant colony optimization approach to solve the time cost trade-off problem in optimizing the schedule of construction projects. Weighting parameters were assigned to the respective objectives of time and cost to convert the multiobjective into a single objective function. A prototype of the ACO approach was developed in a Visual Basic platform and the algorithm showed good search ability without utilizing much computational resources.

Time cost trade-off analysis is one of the most frequently studied problems in project management. Feng, Liu and Burns (1997) created a computer program called TCGA with an Excel worksheet for front data entry to execute a multiobjective optimization using a genetic algorithm and a Pareto front approach. Genetic algorithms belong to the class of evolutionary computation algorithms which imitate the process of natural selection (Gen and Cheng 2000). The concept of convex hull from convex optimization field was defined in this study as a convex boundary that enfolds all individuals in a GA population from below. The distances between the individuals and the convex hull were calculated to determine the fitness of each individual in the GA iteration, and subsequently the possibility of surviving to the next generation. The underlying principle is that individuals that are closer to the convex hull have better fitness, and will guide the new population to move towards the convex hull.

Particle swarm optimization (Clerc and Kennedy 2002) is another metaheuristic approach which mimics the behavior of birds flocking to a target position. Similar to GA, the PSO algorithm starts with randomly generated initial populations and iteratively updates the solutions to improve performance. Zhang and Wang (2008) presented a particle swarm based optimization methodology to solve the construction site facility layout problem. The objective function of total cost including the communication cost and setup cost, was formulated to evaluate the candidate solutions of the construction site layout. The communication costs cover the cost for material flow as well as material handling between facilities. A computational experiment of a site layout problem with eleven facilities and eleven locations was performed using the proposed PSO approach and a GA method. With the same fitness function, the result showed that the PSO algorithm had better convergence properties and required fewer iterations to allocate the optimum compared to the GA method.

3.4 Simulation-based Optimization Approaches

Many systems in the industry are too complex to be modeled analytically. With advances in computer technology over the last few decades, it is possible to develop new techniques for evaluating the performance of such industrial systems. Simulation has been extensively used in many areas of civil engineering as well as in the construction industry in recent years.

3.4.1 Simulation of Construction Operations

Construction operations possess linear properties since the work processes need to be completed in a particular sequence (Halpin and Riggs 1992). Even though each construction project is unique, many processes are repetitive. Taking the construction of a high rise building as an example, one floor needs to be built before constructing another floor on top, and the work process of building each floor normally does not vary much. Hence, the
repetitive sequence and the cyclic nature make the operations suitable to model with the help of simulation. Discrete event simulation (DES) technology has gained considerable attention in modeling and analysis of construction operations. In discrete event simulation, the activities are processed based on logical relations between process components and the availability of resources. The state of the system changes at discrete and measurable points in time (Law and Kelton 2000). Using a DES modeling approach, the modeled systems become dynamic in nature.

When designing a simulation system, the application extendibility, modeling concept and flexibility are the important factors that should be taken into consideration. Martinez and Ioannou (1999) discussed two main simulation strategies for modeling construction processes: Process Interaction (PI) and Activity Scanning (AS). A PI model is designed for modeling operations where moving entities flow through a system, and this method is preferable for operations where the entities have many attributes and the resources have fewer attributes. Manufacturing and industrial operations are excellent examples of PI processes. On the other hand, an AS model is intended for operations with various activities and focuses on recognizing the activities and the conditions required for the activities to take place. Most construction operations include many interacting resources in numerous states, and the conditions required to carry out activities are best described with logical complexities. The authors therefore claimed that this type of operations will be more easily represented using the AS modeling paradigm.

In the early 1970s, Halpin (1977) introduced the CYClic Operations NEtwork (CYCLONE) modeling methodology which modified the conventional Activity Cycle Diagram (ACD) to indicate various activities that take place in construction operations. Six basic elements shown in Figure 3-1 are predefined to model the cyclic and repetitive activities in construction operations. Because of its clear and simple symbolic structure, it is undoubtedly the most commonly employed in the modeling of construction operations. Readers may refer to Halpin and Riggs (1992) for details and a deeper understanding regarding the CYCLONE modeling methodology.

A further development was the creation of the software tool MicroCYCLONE (Lluch and Halpin 1982) in the 1980s. Today, the MicroCYCLONE software is replaced by a similar program named WebCYCLONE which is available online1 at Purdue University, West Lafayette in the United States for various users.

One limitation of the MicroCYCLONE and WebCYCLONE simulation programs is the inability to explicitly specify the resources. In other words, it is not possible to distinguish between resources with diverse properties. For instance, the hauling fleet consists of two different hauler models, and it is not possible in the simulation to specify the different capacities and hauling times of the two hauler models.

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1 https://engineering.purdue.edu/CEM/People/Personal/Halpin/Sim/index_html
Normal activity

Combination activity (Combi)

Queue node

Function node

Arrow

Counter

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal activity</td>
<td>![Symbol]</td>
<td>Unconstrained activity. Entities arriving at a Normal node will be processed directly without delay.</td>
</tr>
<tr>
<td>Combination activity (Combi)</td>
<td>![Symbol]</td>
<td>The constrained work task modeling element. It is logically constrained in its starting logic but otherwise similar to the normal work task modeling element.</td>
</tr>
<tr>
<td>Queue node</td>
<td>![Symbol]</td>
<td>The idle state of a resource entity symbolically representing a queuing or waiting for use of passive state of resources.</td>
</tr>
<tr>
<td>Function node</td>
<td>![Symbol]</td>
<td>The Node performs special function such as consolidating, marking and statistic collection.</td>
</tr>
<tr>
<td>Arrow</td>
<td>![Symbol]</td>
<td>The resource entity directional flow modeling element.</td>
</tr>
<tr>
<td>Counter</td>
<td>![Symbol]</td>
<td>Keeps track of the number of times units pass it.</td>
</tr>
</tbody>
</table>

Figure 3-1. The basic CYCLONE modeling elements

Martinez (1996) extended CYCLONE and created an advanced simulation software called STate and ResOurce Based Simulation of Construction ProcEsses (Stroboscope). With its user-friendly graphical interface, the Stroboscope software can dynamically determine the state of simulation and the attributes of resources in a construction operation. The state of simulation represents factors such as the number of trucks waiting for loading, the number of times an activity has occurred, and the last time to commence a specific activity, etc. The program also allows the user to model activities and resources with detailed attributes such as the priority of an activity, queuing discipline and so on. The Stroboscope is an extendable system designed for modeling complex construction operations in details. To meet the need for an easy-to-learn and simple tool for analysis of construction processes, Martinez (2001) also developed another graphical simulation program called EZStrobe. EZStrobe is based on Stroboscope, but excludes the possibilities of uniquely identifying resources and incorporating extremely complex logic. Both Stroboscope and EZStrobe are available for download at the EZStrobe homepage\(^2\). These two programs have been used for productivity estimation and comparing different process alternatives in numerous construction projects, such as tunneling operations in Ioannou and Martinez (1996), lean construction techniques (Tommelein 1998), and asphalt paving operations (Hassan and Gruber 2008).

Most of construction operations consists of equipment-driven processes. Shi and AbouRizk (1997) proposed a resource-based modeling (RBM) method for construction simulations using resources as the basic building blocks. The resource concept covers various kinds of

\(^{2}\) http://www.ezstrobe.com/
equipment such as excavators, loaders, haulers/trucks, graders, compactors etc. Subsequently, Shi (1999) proposed an activity-based construction (ABC) modeling concept which only used one single element (activity) for modeling general construction processes. The ABC method included all necessary functionalities as activity attributes, while the other modeling methodologies such as ACD and CYCLONE incorporated these aspects through various additional modeling elements. Compared to the other two methodologies, Shi (1999) demonstrated that it was in general easier and more practical to model various operations using the ABC method. Shi also reasoned that since activity attributes are directly associated with the specific activity, it was hence simpler and more intuitive for the user to describe the local environment of the activity than to model it using other elements as for instance in CYCLONE modeling method. The ABC simulation method was further developed and an animation function was introduced to provide a possibility for the user to observe the sequence of events and the interactions between resources during the simulation time (Hong, Shi and Tam 2002), (Zhang, Shi and Tam 2002). The users may visualize the system dynamics and status changes of a construction process, and gain a better understanding of the simulated system.

All above-mentioned simulation software products are based on general purpose simulation methodologies. These systems are general in nature and allow the users to build various models of operations using abstract elements. In Hajjar and AbouRizk (1997) and AbouRizk and Hajjar (1998), the authors argued that although these general purpose simulation systems are flexible and powerful from an academic point of view, most of the practitioners who can benefit from them do not possess the required knowledge. In practice, the managers have to either spend several weeks or days to learn the modeling techniques, or hire simulation consultants to perform the required analysis. The authors hence proposed a special purpose simulation approach with a computer-based visual environment call AP2-Earth, which allows practitioners with knowledge in a specific domain but not in simulation, to model for instance an earthwork project. The AP2-Earth simulation tool had symbolic elements which resemble the reality representing the operation environment (pile of earth, hauling road segment, maintenance facility etc.), the resources (loader, truck etc.) in construction operations, so that the practitioners could visually build an unlimited number of models. This software employed the process interaction concept and was specially designed for the practitioners with knowledge and field experience in earthwork operations.

Extending the work on AP2-Earth, another simulation tool called Simphony (Hajjar and AbouRizk 1999), (AbouRizk and Mohamd 2000) was developed for the modeling and analysis of construction operations in general. Besides the simulation template with graphical user interface, Simphony also included a general purpose template that enabled the users to build models according the CYCLONE methodology. Thus, the CYCLONE template had a more comprehensive and complete tool definition and compilation environment, and users with knowledge in general purpose simulation could create models with high flexibility for specific uses. Similarly to the AP2-Earth simulation, the template with symbolic elements resembling the reality provided an intuitive and user-friendly tool for the construction planners. The creation of Simphony software is an excellent example of simulation tools
suitable for both academic and industry applications. AbouRizk (2010) reported that the Simphony program was recently licensed to DRAXWare Inc. and had been adapted to commercial software for construction operations.

Many other successful applications of simulation in the construction industry and collaborations with academia have been reported. It was stated in Halpin and Martinez (1999) that there were over 20 universities in the U.S. and Canada that offered construction simulation using the CYCLONE method or other modeling techniques as regular courses at both the graduate and undergraduate levels. Examples of other simulation programs for construction operations are COOPS (Liu and Ioannou 1992), DISCO (Huang, Grigoriadis and Halpin 1994), CIPROS (Tommelein, Carr and Odeh 1994), PROSIDYC (Halpin and Martinez 1999).

In conclusion, computer simulation has some major advantages compared with analytical methods. First, simulation has a dynamic nature and can catch the interactions between resources. Second, simulation can take into consideration the randomness of a real world system. However, it is not an easy task to model an operation, to build the model using some simulation tools, and to understand and verify the simulation results. As Shi (1999) pointed out, modeling is both science and art. It involves converting the reality to abstraction and finding solutions; furthermore the abstracted solutions need to be understood, translated back into reality and articulated. This requires that the user understands the dynamic and stochastic features of the process before constructing a simulation model. Statistical knowledge and in-depth site observations are needed to guarantee the accuracy of the input data. Also, verification of the simulation model and validation of the results require comprehensive skill and experience.

A graphic interface makes the process of building simulation model easier, but the users still have to possess necessary knowledge in simulation. Modelers can build a library containing simulation models of most common processes. Such libraries are efficient and increase the reusability of simulation models, but the downside is that all possible operations may not be included in the library due to the uniqueness of construction operations.

Furthermore, animation is one of the most attractive functions of the computer simulation technology. In general, animation can assist the user in understanding the dynamic behavior of the real-world process. In addition, it provides a mean for verification of a simulation model and validation of simulation results.

3.4.2 Simulation-based Optimization

Simulation-based optimization is an emerging field which has received considerable attention in the last decades. The recent development of simulation in construction engineering has provided a great potential for improvement of construction operations. By experimenting with different possible scenarios, simulation can assist the decision-making in determining the best strategy for execution of a specific operation in practice. The development of discrete event simulation software has made the interfaces between operations research and computer science possible. A descriptive review of the main approaches in the simulation-based
optimization field was provided by Fu, Glover and April (2005). The approaches include ranking and selection procedures, response surface methodology, gradient-based procedures, random search algorithms and metaheuristic methods. Depending on the problem at hand, different approaches may be employed. Among the techniques, the ranking and selection approach and the response surface methodology are suitable in solving problems with both continuous and discrete variables. Gradient-based procedures are only applicable to continuous optimization problems. Random search and metaheuristic methods are primarily designed to solve optimization problems with discrete decision variables. A number of examples in construction operations employing the above-mentioned simulation-based optimization approaches are given in this section.

Efficient handling of material flow has been studied frequently in the past decades, and has also been addressed in the construction industry due to the massive quantity of material involved in the operations. An activity-based simulation system was applied by Ng, Shi and Fang (2009) to enhance the logistics of construction materials. To avoid expensive labor and resources staying idle, many managers normally prefer to preserve additional construction materials on site. The authors pointed out the fact that despite the improved productivity and cash flow with a reduced material stock, the construction planners are still not willing to take the risk, especially when the consequences in an operation are not totally clear. The process of delivering and handling massive construction materials for a high-rise residential building construction project in Hong Kong was modeled using an activity-based simulation method. Two different material handling concepts were tested against the existing model to identify the possible savings in time and cost. The authors concluded that there were huge savings in the project duration and the need of storage space with the proper management of material flow.

Smith, Osborne and Forde (1995) combined a discrete event simulation program with a response surface method to study the impact on the production rate in an earthmoving operation. Eleven input variables were included in this study: the mean and variance of hauling units’ traveling time and dump time, the mean and variance of load pass time, etc. A $2^4$ factorial design was applied to determine the level of the chosen factors, and the experiment showed that the production rate obtained from simulation was very sensitive to six factors: number of hauling units, bucket passes per load, load pass time, spot time, hauling time, and dump time. Spot time is also called maneuvering time, and is the time required for the trucks to get from the queue to the position for loading. The authors concluded that the simulation could reflect the interactions between the input factors and could be a useful tool for those with limited experience and expertise in earthmoving operations. Another study employing the simulation software WebCYCLONE and regression analysis for maximizing the productivity of a concrete delivery process can be found in Wang and Halpin (2004).

Still, these methods require the user’s manipulation of input variables, and the optimization searches for a better solution through comparison of exhaustive combinations of alternatives. When the studied problem grows large and complex, it becomes impossible to compute exhaustive enumeration and trial of all possible combinations. Furthermore, most of the before-mentioned optimization methods employed in earthmoving operations assume that
optimizing productivity will in turn minimize the overall production cost. The aspects of cost and profit of a project are thus not examined in these studies.

AbouRizk and Shi (1994) presented an automated framework that incorporated the simulation engine MicroCYCLONE and heuristic methods to guide the system to search for the most appropriate resource allocation for an earthmoving operation. Three objectives were studied in this paper: production maximization, unit cost minimization and reasonable resource allocation. Depending on the particular objective, the authors proposed different techniques to automatically drive the system towards solutions with better performance. For the productivity maximization problem, the delay statistic of resources was used to analyze whether the current resource allocation system is adequate or still needs improvement. The delay statistic of a resource signifies the degree of usage of the resource in a process, and a resource can have more than one delay statistic if it is involved in several activities in an operation. Production rate is restricted by the capacity of the limiting resource, which is identified using

$$\text{Delay}_{\text{limiting resource}} = \min_{\text{all resources } i} \left[ \max_{\text{all waiting locations } j} \left( D_{ij} \right) \right]$$  \hspace{1cm} (1.2)$$

where $D_{ij}$ is the delay statistic for resource $i$ at waiting location $j$. Hence, increasing the quantity of limiting resources could improve the productivity. For the problem of reasonable matching among resources, the parameter of resource delay cost was utilized so that the automated system was led to solutions where the resources with higher operating costs are kept at higher utilization rate. This framework was the first attempt towards fully automated simulation-based optimization studies in the construction research field. However, the work was based on the authors’ extensive knowledge and experience in the construction field and the solutions of three objectives were manipulated separately.

Marzouk (2002) presented a comprehensive simulation-based optimization study for optimal fleet selection of earthmoving operations utilizing computer simulation and a genetic optimization algorithm. The five components of this simulation-based optimization system named SimEarth were an earthmoving simulation program, an equipment cost application, an equipment database application, a genetic algorithm for optimization, and an output reporting module. The earthmoving simulation program was designed using the discrete event simulation methodology together with object-oriented modeling to create a graphical user interface. The uncertainty associated with earthmoving operations was also taken into consideration in the simulation engine. The equipment database stored all equipment-related information, and the cost application component was designed to estimate the owning and operating cost of earthmoving operations. In the optimization component, a genetic optimization algorithm was developed to search for an optimal fleet combination with respect to the total project cost or duration. The optimization algorithm provided many advanced options for the genetic algorithm such as fitness normalization, elitism, and storing chromosomes in order to prevent conducting simulation repeatedly for the same chromosome, and finally selecting an optimal fleet. The SimEarth system was further developed by

A similar simulation-based optimization study using genetic algorithms can be found in Cheng and Feng (2003). The authors developed a system called Genetic Algorithm with Construction Operation Simulation Tool (GACOST). All activity durations were assumed to be deterministic in this study to eliminate the influence from uncertainty in the optimization procedure. Subsequently, Cheng, Feng and Chen (2005) proposed a hybrid mechanism that integrated some heuristic methods and a genetic algorithm to efficiently find the best resource combination for construction operations. They claimed that even though the heuristic approaches (HA) can normally generate better solutions in construction operations, the solutions obtained are however not global minima. Additionally, the performance of heuristic approaches can sometimes be problem-dependent. Genetic algorithms perform well in seeking the optimal solution. But GAs conduct a population-wise search, which often needs an enormous amount of computations. The performance of GAs may also depend on the initial population which is randomly generated. The authors suggested a hybrid mechanism that first applied heuristic approaches to find several local minimum solutions and then employed GA to search for the global optimal solution from the local optima. This heuristic genetic algorithm (HGA) was described in detail in the article. The authors gave a test example of how a construction operation was optimized using HA, GA and HGA. Two objective functions were defined: maximizing the production rate and minimizing the unit cost. Results presented in the article showed that this new hybrid mechanism not only located the optimal solution but also reduced computational efforts enormously.

Feng, Liu and Burns (2000) presented a hybrid approach that combines simulation with a genetic algorithm to treat the time cost trade-off problem in construction projects. Unlike their previous work (Feng, Liu and Burns 1997), the stochastic nature of activity durations and costs in a project was taken into consideration in this study. The concepts of Pareto front and convex hull were again employed to guide the genetic algorithm to converge to the optimal solutions in terms of time and cost. However, the convex hull was redefined as the mean values of the project durations and costs of the individuals in each GA iteration, and the fitness of an individual was measured as the individual’s average minimum distance to the convex hull. The authors reasoned that some activities in a project are more risky than others, and adding the stochastic aspect allows the construction managers to analyze different time/cost decisions in a more realistic manner.

Zhou, AbouRizk and AL-Battaineh (2009) used a genetic algorithm to tackle the site layout optimization problem based on various constraints and rules. The construction simulation software Simphony was employed to model spatial site conditions, logistics and resource dynamics of a utility tunnel construction process. Having the Simphony program as input medium, the simulation-based optimization procedure then used a genetic algorithm to search for an optimal site layout with the minimum total transportation cost between site facilities.

All before-mentioned optimization studies were designed to conduct simulation for one particular operation and optimize the performance. To test various operation schemes,
different simulation models have to be constructed before running the optimization procedure. Cheng and Yan (2009) created a mechanism that incorporates a so-called messy genetic algorithm and a simulation engine to optimize resource utilization with respect to the production rate or unit cost. This mechanism could automatically generate various working schemes of the earthmoving operations and build the necessary components for conducting simulation in each scheme, so that the optimization was performed on all possible schemes of the earthmoving operation.

Zhang (2008) formulated a multiobjective optimization problem for earthmoving operations and incorporated an activity-based simulation model, multi-attribute utility theory, a statistical variance reduction procedure and a particle swarm optimization algorithm to look for potential equipment configurations. The performance of different fleet combinations was transformed to a multi-attribute objective function that reflected the preference of decision-makers. A statistical two-stage ranking and selection method for variance reduction was introduced to handle stochasticity in the performance.
4. Contribution of the Thesis

The work described in this thesis has been presented in scientific publications which are summarized in this chapter.

Paper I. A Microscopic Simulation Model for Earthmoving Operations

Simulation is a widely used tool in operation research and system analysis. The popularity of simulation comes from its ability to model complex systems. Simulation provides realistic representations of the interactions among the systems’ various components while accounting for key uncertainties in the operating environment. Discrete event simulation has been used for modeling cyclic processes but also for quantitative analysis of complex construction operations. Examples of simulation software for construction operations based on discrete event simulation modeling methodology are given in Section 3.4.1. However, these simulation systems are all macroscopic, i.e. designed for productivity analysis at the strategic level. There are a number of limitations, especially for uses related to productivity estimation at the operational level. Examples of limitations include:

- Durations of activities are either deterministic or drawn from stochastic distributions estimated from historical data or field measurements. They are not adapted to a fast-changing construction environment and not available for new operating conditions.
- Fuel costs have become a substantial part of operating costs in recent years due to the scarcity of fossil resources and stricter environmental policies, but this aspect has not been taken into account in previous work.
- The fleet at construction sites often consists of vehicles of different types and models with varying capacities, which results in different durations and fuel consumptions for carrying out an activity. However, most of the existing simulation programs do not characterize features such as the make/model of a piece of construction equipment.

In paper I (J. Fu 2012a), a microscopic discrete event simulation system is proposed for modeling earthmoving operations and conducting productivity estimations on an operational level. The logistics of the earthmoving system are represented using the CYCLONE modeling elements given in Section 3.4.1. Discrete event simulation techniques are used to capture the interactions between the resources as well as the randomness of each of the activities. Compared to previous work given in Section 3.4.1, this microscopic model represents individual equipment at a very detailed level, and comprehensive vehicle dynamics are employed to obtain the duration and fuel consumption of each earthmoving activity. The vehicle dynamics incorporate the impact on performance of several factors such as characteristics of earth, road geometry and vehicle payload, and provide accurate estimates of activity duration and fuel consumption. These estimates are then used as input to the discrete event simulation. Subsequently, suitable probability distributions based on previous studies of durations and fuel usage are used to describe the randomness of these two aspects. In addition, the simulation module also includes the flexibility to characterize resources.
A prototype is developed to demonstrate the applicability of the proposed simulation framework, and the simulation system is presented via a case study based on an actual earthmoving project. The case study shows that the proposed simulation model is capable of evaluating alternative operating strategies and resource utilizations at a very detailed level. It supports a better understanding of the interactions between resources, and the impact of improvements in the operating characteristics of equipment, operator behavior etc.

**Paper II. Simulation-based Optimization of Earthmoving Operations using Genetic Algorithm**

Paper II (J. Fu 2012b) presents a framework for simulation-based optimization of equipment selection for earthmoving operations by integrating a simulation system and a genetic optimization algorithm (GA). An optimization problem with the objective of minimizing the Total Cost of Ownership (TCO) of the earthmoving operations is formulated, subject to a minimum productivity requirement and a maximum number of equipment units in the operations, defined by the user. The logistics of earthmoving operations are modeled using the discrete event simulation model presented in Paper I and simulated through a newly developed simulation system for estimating the cost, productivity as well as resource utilization of earthmoving operations. A genetic algorithm is then employed to search for a near optimal equipment configuration that gives the lowest TCO while considering a set of qualitative and quantitative decision variables which influence the performance of earthmoving operations. Qualitative variables refer to the models of equipment, while quantitative variables represent the number of equipment units used in each fleet scenario. The discrete event simulation system evaluates the fitness of each equipment combination and then GA performs the selection, crossover, mutation procedure and generates the new offspring according to the fitness values. The fitness values of the new offspring are again determined by conducting discrete event simulation. The simulation-based optimization process is repeated until the termination condition is reached.

A computer program is developed to demonstrate the applicability of the proposed simulation-based optimization framework. Pilot simulation runs show that the simulation model is capable of evaluating alternative operating strategies at a relatively detailed level and supports a better understanding of the interactions between resources. The GA optimization shows good convergence properties and can effectively locate a local optimal equipment combination for earthmoving operations. The proposed simulation-based optimization framework can hence serve as an efficient tool for the project management in equipment selections for earthmoving operations.

**Paper III. Optimal Fleet Selection for Earthmoving Operations**

In Paper III (Fu and Jenelius 2013), the work in Paper II is extended and an optimal fleet selection problem is formulated where the performance of earthmoving operations is measured using the TCO concept and productivity. Productivity is defined as the output per unit time from the entire fleet and is one of the most commonly used objectives in
construction business. Further, a two-stage ranking procedure is introduced in the GA to further improve the performance of the optimization algorithm.

Taking the TCO minimization problem as an example, a fleet with the same TCO value and higher productivity is preferred over the one with lower productivity. Hence, the productivity is considered as the second aspect in the ranking process in the optimization algorithm. The fitness of the population in each GA iteration is first arranged according to the objective value of TCO, and then ranked again by their productivity. In this manner, for fleet combinations with the same TCO values, the one with higher production rate will have higher rank and hence higher probability of being selected to produce offspring. For the productivity maximization problem, the TCO value is chosen as the criterion in the second ranking procedure. Intuitively, lower TCO for the same production rate indicates lower production cost.

In contrast to using a multi-objective formulation of the problem, this two-stage ranking procedure allows the user to define the objectives of a project on two levels of priority. First of all, the user does not need to test different weighting parameters of each objective before obtaining a satisfactory result. Second, the method can find fleets with better overall performance compared to single objective optimization. The two-stage method is thus more straightforward and less computationally demanding for construction management applications.

Numerical examples of TCO minimization and productivity maximization are given to demonstrate the effectiveness of the proposed simulation optimization framework with the two-stage ranking procedure.

**Paper IV. Gear Shift Optimization for Off-road Construction Vehicles**

Fuel efficiency has become one of the main focuses for automobile manufacturers. In recent years, several studies have been carried out to examine the possibility of improving fuel efficiency utilizing topographical information and positioning system to aid look-ahead control systems for road vehicles. However, these methods have not yet been investigated on off-road vehicles such as construction equipment due to unavailability of topographical maps of the operating environments. Paper IV (Fu and Bortolin 2012) presents a gear shift optimization problem for off-road construction vehicles using an optimal control algorithm.

The paper explores the possibility of using recorded road topography information together with a GPS unit to minimize fuel consumption and travel time for construction vehicles such as articulated haulers. An optimal control algorithm which incorporates a model predictive control (MPC) technique and dynamic programming (DP) is formulated to find an optimal gear shift sequence as well as the time of shifting. Weighting parameters are introduced to balance the trade-off between the fuel consumption and the total travel time in a single objective function.

First, a dynamic model of an articulated hauler’s powertrain is derived. The vehicle dynamic model takes the gear sequence, throttle input, brake input, and road topographical information
as inputs and outputs the vehicle’s velocity, fuel consumption and engine speed. The proposed MPC controller uses the vehicle dynamics and the recorded road slope data to predict the future values of certain relevant states over a limited position horizon just ahead of the vehicle. These predicted states are then utilized in a discrete dynamic programming algorithm to find an optimal gear shift sequence as a function of the vehicle future position for the particular prediction horizon. Then the first steps of the control strategy are implemented over a shorter control horizon. The state of the system dynamics is measured again and the whole procedure – prediction and optimization – is repeated to obtain new control inputs with the prediction and control horizon shifted forward.

The proposed optimal control algorithm is tested and evaluated against the current gear shift strategy through computer simulation with Volvo CE’s in-house simulation software. The simulation software includes complex dynamics of articulated haulers and is regarded as highly accurate. The simulation results show that both fuel consumption and travel time can be reduced simultaneously using the proposed control algorithm. Prior to an uphill slope, the control algorithm chooses to shift down to accelerate so that the hauler will have a higher torque to climb the hill. Before a downhill slope, the controller shifts up to slow down the vehicle speed which is an intuitive way of saving fuel. The gear shift sequence obtained from the optimal control algorithm resembles the behavior of an experienced driver.
5. Conclusions, Discussion and Future Research

5.1 Conclusion

This thesis develops a simulation system for modeling earthmoving operation and conducting productivity estimations on a microscopic level. The case study given in Paper I shows that the simulation system can represent the earthmoving operations on a detailed level and is a suitable tool for the project managers to estimate productivity and compare alternative operating methods on the operational level.

The simulation is incorporated in a simulation optimization framework presented in Paper II and III to search for an optimal fleet combination for earthmoving operations. Two different objectives, TCO minimization and productivity maximization are formulated and demonstrated via case studies. The numerical examples show that the proposed framework can efficiently allocate a local optimal fleet configuration of construction machinery for the specified objective. Unlike previous optimization studies mentioned in Section 3.4.2, this framework is able to not only decide an optimal number of equipment, but also the type and capacity of the equipment.

We also study the possibility of reducing fuel consumption for articulated haulers given that the hauling route topographical information is known. An optimization problem is formulated to find an optimal gear shift sequence and time of shifting which minimizes an objective function of fuel consumption and travel time using weighting parameters. The optimal control problem is solved using a Model Predictive Control algorithm together with Dynamic Programming technique. The simulation results show that both fuel usage and total travel time for a driving task can be reduced simultaneously using the proposed optimal control algorithm.

5.2 Discussion and Future Research

The work we presented in this thesis shows that it is feasible to improve the overall performance of earthmoving operations using simulation and optimization methods in the planning process. However, there still remain many aspects to be investigated and solved.

One of the issues that need further investigation is the validation of the proposed simulation model. Using the logistics of an earthmoving operation with the same activity durations, the simulation system described in Paper I is verified against two other independent simulation software, WebCYCLONE and Stroboscope. However, the simulation model is not validated to real earthmoving operations due to the unavailability of field data. The validation of the simulation model requires a large number of field data and yet we have not means to collect data at the construction sites efficiently.

Another aspect that needs consideration is the validation of optimality of the obtained solution in the optimization problems. After the optimization algorithm converges to a fleet
configuration, the nearby points in the search space are tested using simulation to confirm the recommended fleet is a local optimal. However, the global optimality of the obtained solution is not guaranteed. A possible way may be to conduct simulations for all possible fleet combinations and thus to confirm the global optimality. However, this will require a systematic way to compute all possible fleet combinations and it might be quite computationally time-demanding.

Moreover, this thesis only addresses the optimal fleet selection problem for earthmoving operations with a pre-defined operating method. We could increase the scope of the optimization problem by investigating different operating methods, e.g. employing a fleet consisting of loading and hauling units or more independent machines such as wheel loaders and scrapers.

An amount of research has been focused on the modeling and optimization of earthmoving operations, including this thesis. However, increasing attention is and will be given to even more challenging problems such as site layout optimization, stochasticity of the objective function and constraints, dynamic nature of construction operations.

The layout of construction site is essential to any construction projects and has a significant impact on the economy, efficiency, safety, and many other aspects. Especially for large construction projects, the savings can gain from efficient layout design should not be disregarded. In the further research, we could formulate a site layout problem and investigate the optimal locations for each working stations in earthmoving operations.

In stochastic optimization problems, some variables have a stochastic nature which in turn affects the value of objective function. This aspect is only taken into consideration in the TCO minimization problem in Paper II, and the optimization algorithm is able to converge to the same fleet combination in both deterministic and stochastic case. The performance of the proposed optimization algorithm in productivity maximization problem is yet to be examined. The numerical examples in Paper III showed that there were several fleet combinations with the same production rate, and this might cause problem for the optimization method.

The dynamic problems are characterized by the fact that the search space in optimization changes during time. In earthmoving operations, the loading stations tend to move further away from the dumping station during a work process. As the hauling path getting longer and the geometry of the haul route changes, the previous optimal fleet combination may not be optimal any more. In such a situation, it is crucial that the algorithm be able to follow the changes in the operating environment and adjust the search direction. In recent years, GPS device has become a standard equipment for the construction equipment. The measurements from GPS receiver and onboard sensors of vehicles could be utilized to estimate the road topographical information (Sahlholm 2001). This 3D map building method will provide road grade estimates which can be used for instance in the gear shift optimization problem in Paper IV. Moreover, the road grade estimates and GPS localization can catch the changes in a construction environment, so that the optimization algorithm could follow the dynamic environmental changes and thus modify the search space accordingly.
References


Site simulation tutorials. Volvo Construction Equipment.


