Enhanced Tower Crane Operations in Construction Using Service Request Optimization

Arman Shamsmolavi

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Prof. Dr. Serhan Çiftçioğlu
Acting Director

I certify that this thesis satisfies the requirements of thesis for the degree of Master of Science in Civil Engineering.

Prof. Dr. Özgür Eren
Chair, Department of Civil Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Civil Engineering.

Assoc. Prof. Dr. İbrahim Yitmen
Supervisor

Examining Committee

1. Assoc. Prof. Dr. Umut Türker

2. Assoc. Prof. Dr. İbrahim Yitmen

3. Asst. Prof. Dr. Serhan Şensoy

ABSTRACT

Tower cranes are one of the most important equipment in the construction sites, by the time passing the role of the tower cranes will be more significant. Tower cranes are among the most expensive machines. By enhancing the usage of tower cranes time and cost will be reduced, and the quality and safety will be improved.

Everyday tower crane's operator has a list of request from crews, he/she must take materials that they need from specific storage and carry them other location. Usually operator himself/herself decide which crew will get their material first which one is second and so on, and of course it is not the optimum sequence. Since that activity that related to tower crane are mostly on the critical path, if delay happens in these activities it will effect duration of the whole project. So by enhancing the service request sequence both time and cost will be reduced.

In this study MATLAB R2013a software is used, and to find the optimum solution a Genetic Algorithm is coded. In this example 9 best solution were find within 50! Different alternative answers, so construction manager according to the situation can decide which service request should be used.

Keywords: tower crane, optimization, stable solution, crane service request problem

ÖZ

Kule Vinçler şantiyelerde kullanılan en önemli ekipmanlardan biridir ve geçen zaman içerisinde rolleri daha da önem kazanacaktır. Kule Vinçler en pahalı makineler arasında yer almaktadır. Kule Vinçlerin kullanımı ile zaman ve maliyet azalacak ve kalite ve güvenlik geliştirilecektir.

Günlük olarak kule vinç operatörüne ekiplerden gelen bir istek listesi vardır. Operatör, ihtiyaç olan malzemeleri belirli depolama alanından alıp diğer konuma taşımak zorundadır. Genellikle operatör kendisi malzemeyi ilk alacak olan ekibin hangisi olacağına ve sonrasındakilere karar verir ve tabii ki bu en uygun bir sıra değildir. Kule vinç ile ilişkili olan aktiviteler genellikle kritik yol üzerindedir ve bu aktivitelerde yaşanan gecikmeler tüm proje süresini etkileyecektir. Bu yüzden hizmet isteği sırasını artırarak zaman ve maliyet azaltılabilir.

Bu çalışmada MATLAB R2013a yazılımı kullanılmış ve en uygun çözümü bulmak için veriler Genetik Algoritma ortamında kodlanmıştır. Bu örnekte 50 (elli) farklı alternatif cevaplardan en uygun 9 çözüm bulunmuştur, böylelikle yapım yöneticileri duruma göre hangi hizmet isteğinin kullanılacağına karar verebilmektedirler.

Anahtar kelimelr: Kule vinç, optimizasyon, sabit çözüm, vinç hizmet isteği sorunu

To My Lovely Family

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LIST OF SYMBOLS

T_r	Radial Travel Time of Tower crane (sec)
T_a	Angular Travel Time Tower crane (sec)
T_h	Hoisting Travel Time (sec)
V_a	Angular Velocity
V_r	Radial Velocity
λ	Internal parameter skill worker
μ	External parameter skill worker
σ_x	Standard Deviation of Waiting time of the crews
σ_x^2	Variance of Waiting time of the crews
N	Total number of alternative
μ_x	Average

LIST OF ABBREVIATION

GA	Genetic algorithm
PAES	The Pareto Archived Evolution Strategy
SPEA	Strength Pareto Evolutionary Algorithm
NSGA-II	Non-dominated Sorting Genetic Algorithm-II
MOGA	Multi Objective Genetic Algorithm
Micro-GA	Micro Genetic Algorithm

Chapter 1

INTRODUCTION

1.1 Background

Tower cranes are being widely used in construction sites; one of the most costly and essential machinery resources in a typical construction site. Tower cranes are widely used for transportation, lifting, and delivering materials, especially with heavy weights or massive volume in construction projects. Tower cranes can lift and transfer heavy materials and deliver them to the crews or the location that they are needed. Height of these machines can be more than 80 meter without support; and it can be higher if it is fixed to the structure. Their maximum diameter for material delivery is 70 meters, and their maximum lifting power is 19.8 ton. By increasing the distance of materials from the cabin, tower cranes' capacity will reduce (300 ton-meter) according to the investigation done by Parker, Smith, and Hogan (1992). Tower cranes are widely used in warehouse, construction site, harbors, and etc. These machines are useful in construction sites especially in building skyscrapers, and high-height structures. Tower cranes can lift cement, concrete, steel, etc. in construction site.

1.2 Literature review

Nowadays, tower cranes are among the most important lifting machines, which can be used everywhere such as: construction site, harbors, train stations, warehouses and etc. If any delay occurs in delivering a material to a construction team then it will endanger the project of delay penalty. The popularity of tower cranes' usage makes the tower crane operation more important since any default or failure in running the tower crane in a project leads into diverse effect on project cost, time, quality, and safety. This significant role of tower cranes attracts the attention of the researchers. Table 1 shows the classification of tower crane studies.

Table 1. Classification of tower crane researches

Subject	Researches
Safety and productivity of tower crane	(Everett & Slocum, 1993; U. K. Lee, Kang, Kim, & Cho, 2006; V. W. Tam & Fung, 2011)
Best location of tower crane	(Huang, Wong, & Tam, 2011; C. Tam & Tong, 2003; C. Tam, Tong, & Chan, 2001; Zhang, Harris, & Olomolaiye, 1996)
Optimum number of tower crane	(Furusaka & Gray, 1984; Ho, Kim, & Kook, 2007)
Optimizing time of using tower crane	(Zavichi & Behzadan, 2011; Zavichi, Madani, Xanthopoulos, & Oloufa, 2014)

1.2.1 Optimization of tower crane by improving service requests

Tower cranes are one of the most expensive equipment that has widely been used in shipyards, warehouse, and construction sites. Despite a vast usage, tower cranes are not modern in terms of automation and technology. A typical tower crane is often operated by a person in the cabin that controls the tower crane and another person on the ground for enhancing the visual and safety in order to avoid collision. The person that controls the tower crane has the responsibility to set priorities for delivering materials to each group. Therefore, it may cause a delay in jobsite, in a long term it will increase time and cost of the project and it can change the critical path. Zavichi and Behzadian (2011) and Zavichi et al., (2014) tried to optimize the time by developing a decision support system which evaluates and find the best way to deliver the requests using the most efficient sequence order.

Zavichi et al. (2014) Investigated the optimization of tower crane by improving service sequence. They used Travel Salesman Problem (TSP) formulation for optimizing the construction tower crane operation. Using optimization for tower crane they managed to save 25-40% in time and cost of using tower crane. However, in their study, only time of the project was considered since it was assumed that reducing the time of using tower crane will reduce the cost and time of the project.

1.2.2 Allocating tower crane

Allocating each crew and material storage is a complicated issue in the construction site, changing the place of each member will cause change in utilization of tower crane and time and cost of the project. Because of the large number of crews and material storage, there is an infinite ways that they can be located, placing each one in a correct location is vital (Huang et al. (2011); Zavichi et al., 2014)**.** Huang et al. (2011) tried to define area of construction in order to address the difficulties in selection of appropriate locations for the warehouses. Their research study aimed to optimize tower crane and supply location by developing a genetic algorithm optimization model.

Tam and Tong (2003), published a research study developing an artificial neural network to model the non-liner operation for tower crane, and for allocating tower crane, demand point and supply points. They used genetic algorithm for optimizing time and cost of the transportation.

1.2.3 Improving the productivity and safety

Simulation of the construction site can be useful by giving a visual idea, so construction manager can see and feel the improving and managing project. Al-Hussein, Niaz, Yu, and Kim (2006) showed that 3D visualization and simulation helps planning, modelling and decision making in complex construction. Special Purpose Simulation (SPS) and 3D visualization of simulated operations help construction managers to fulfil their demand of controlling construction site with computer tools. By 3D visualization managers can analyze their project easily. In that research study, researchers present a practical methodology for integrating 3D visualization with SPS for tower crane operation, using 3D studio MAX environment.

Tower crane operates with a person in the cabin of the crane and usually another person with Walkie Talkie, to give information to operator. Crane operator does not receive enough information such as the distance and condition of the materials being loaded. This causes the productivity and safety of construction site to be reduced. U. K. Lee et al. (2006) presented a way that increases the safety and productivity of tower cranes by using advanced tower cranes (ATC). ATC are equipped with wireless radio frequency identification (RFID) and wireless video control. By using this technology operator, has a better view of the work space and updated materials can be achieved. It also improves the safety and speed of tower crane.

As it was mentioned earlier, tower cranes are one the most important equipment on the work places. However, navigation technology for passing the materials that is loaded in the crane has not been improved. Operator frequently cannot see the load since it needs someone else to inform the operator from existing obstacles. Everett and Slocum (1993), presented CRANIUM, CRANIUM as a video system for improving productivity and safety by enhancing communications. A camera was located at the end of the crane boom and with one monitor inside a cabin operator to see the load. It shows that using CRANIUM increases the productivity by 16-21% and improves the safety as well.

Tower crane operator deals with blind situations. Recently, video camera system and anti-collisions system are being used for solving this problem. However, in this system operation, it does not have an accurate information about the distance of the load from surrounded obstacles and collision system. This only gives data in a numerical form which is then imported into the model. G. Lee et al. (2012) presented a newly developed tower crane navigation system which operates on accurate information about the surroundings and position of the object and buildings in a real time using sensors and building information modelling (BIM) model. This model applies solution from two points of view, "ease of use" and "usefulness" based on the Technology Acceptance Model (ATM) theory. According to experience, using this system in a tower crane on the site for 71 days, this method improved ease of use from 3.2 to 4.4 through an iterative design process, and operator could relied on the navigation system during blind lifts (93.33%) compared to old system, anti-collision system (6.67%).

Most of the construction sites are usually very close to public sectors. Tower cranes accident not only hazarded for workers and construction site; but also hazarded pedestrians.V. W. Tam and Fung (2011) investigated a tower crane safety in Hong Kong construction industry. They gathered their information that needed by a questionnaire survey. They found that human factors has a big portion in crane safety. One of the main reasons that reduce the crane safety is inadequate training and fatigue of the operator. In this study, recommendations for increasing safety are discussed.

By increasing the number of high-rise building, there is the need to increase and nowadays efficiency and safety have big role in construction trades.G. Lee et al. (2009) developed a new system for tower crane that is using the laser robots for controlling crane. By using robotic tower crane system they have shown that the productivity increased by 9.9%-50%. They examined the feasibility of a laser-technology-based lifting-path tracking system for a robotic tower-crane system. This tower crane robotic system had some problems such as travel in a preplanned path and blind stop. In this system there is a device that can receive and records data from lasers.

1.3 Importance

In construction site these factor are the most important factors: time, cost and quality Babu and Suresh (1996). According to Babu et al. (1996) reducing the overall cost and time of the project are both important, however the greatest concern is on the cost. The importance of this subject is its role in decreasing time and cost of the project. For many years, tower cranes are being used, and as time goes by, working with these machines become easier and safer and more efficient. But there is much more work to do to improve the current situation of tower cranes.

1.4 Justification for dealing with tower cranes

Tower cranes are one of the most costly machines in the construction sites, and it is obvious that projects can reduce their costs are more successful U. K. Lee et al. (2006). Activities that depend on the tower cranes usually lie on the critical path. In this research study, it is tried to reduce the overall cost of the project by optimizing the use of tower cranes. The effect of the tower cranes on the project cost is significant, so by reducing the cost of tower cranes, the profit of the project is increased sharply. Especially, when there exist a couple of tower cranes in site, improving the environment of the work place and other things that are related to tower cranes, can became vital in reducing cost and increasing safety.

1.5 Previous researches about tower cranes

Working on tower crane can be interesting from several points of view. One of the most interesting problems in this field is finding optimum number of tower crane that is needed in construction sites. By changing the number of tower cranes, the project cost, time and safety can be affected, however, what is the optimum number? It is obvious that by increasing the number of tower cranes, the project time will be reduced but what about the cost and safety? (Furusaka & Gray, 1984; Ho et al., 2007).

The other problem of tower cranes is their location. The question is that what is the best place for locating the tower cranes? By changing the location of tower cranes safety, time and cost will be changed (Huang et al. 2011; Tam and tong, 2003; 1996). Tam and Tong (1996) demonstrated a way that can show the best place for tower cranes.

One of the most controversial issues related to tower cranes is the safety. Most tower cranes work nearby the public places, therefore if something happens not only work place will be in danger but also it can cause deadly occurs in public places. For dealing with this problem, some works done for increasing safety of the tower cranes by installing camera and improving navigating of the machine, so operator can be aware of the obstacles in the site (Everett & Slocum, 1993; U. K. Lee et al., 2006; V. W. Tam & Fung, 2011).

Moreover, one of the most and effective issues related with tower cranes is ranking the service requests, operator usually deliver materials to each crews by first-in-first-out (FIFO) pattern. That means first group submit its orders will get them sooner, but it is not the best way of delivering materials, changing the priorities of service request can change time and cost of the project (2011; Zavichi et al., 2014) shows that what is the best way to find out priorities of service requests

1.6 Questions to be answered

Previous researchers were concentrated on reducing the overall travel time of tower cranes and also reducing the waiting time of each crew, regardless of the cost of each crew, they tried share waiting time between each group fairly, but what if waiting time of some crews are more costly!?

In the project site, there are several crews and material storages, each crew has a demand from material storage. Tower cranes operator should deliver all the requested materials that each crew needs. If the delivery of materials by this pattern is used, first order first deliver, or following this rule deliver materials to nearest group first, it will waste time and cost. This problem is like travel sale person (TSP), by changing the path that tower cranes will pass, time and cost will change, so the question is finding the best path that has the minimum cost. The minimum traveling path dose not necessary leads into the minimum cost.   In this research study, the aim is to find a way that can reduce the overall cost of project regarding the cost of tower cranes and cost of the waiting time of each group on construction site.

In a previous work done by (Zavichi et al., 2014), if one crew place far from the other ones in service request, this crew always will be the last one that can get their materials. In their research study, it was tried to find some best solutions, so from these solutions project manager can decide which one is going to be used.

1.7 Genetic algorithm

Genetic algorithm (GA) is a method that can find one of the most optimizing solution in decision making problems. GA leads the space to find the best answer by producing population and changing their features and finally reach the best generation. An initial population will be produced and GA by cross over operation or mutation change this population's features. Each population consists of many initial solution that were built by some bits. In each level, GA changes some bits of each member of population, and will save some of them (the ones are better solutions), and will change the rest. This process continues till the best answer will appear (Davis, 1991; Rahmat-Samii & Michielssen, 1999; Schaffer, 1985). Because of randomization process, this method doesn't give us an exact answer when we are dealing with multi-objective problems, since one objective should be sacrificed to increase the condition of other objective, but it will reveal some best of them.

1.8 Limitations

The present study is entangled with a few limitations such as the loading time and the unloading time are not considered. One the most considerable issue is that some crews might need materials more than the capacity of the tower crane. Thus, it is better that the operator delivers all materials to one group in more than one pass or deliver. For example, one part of the requested material that one crew needs is delivered first and it is repeated as any time needed to complete the material delivery request. It goes further if some crews need same further material. For example group A need 25 ton Sand, group B need 8 tons gravel and group C needs 10 tons of sand, and the capacity of the crane is 18 tons. Regarding the location of each one best path will change, in this research study just considered crews' needs different material and the amount will be less than the capacity.

Furthermore unexpected problems in this case study aren't considered. For example if it's time to deliver materials to one group and their material is not ready or if some groups add requests that will change the path of the crane's hook.

1.9 Thesis structure

The remaining of this thesis has been structured as follows: In the chapter 2, the proposed methodology has been described and explained in details. In chapter 3, the description of the case problem has been given which illustrates a construction site with single tower crane to give service requests to 8 construction teams from 6 material warehouses. In chapter 4, the results obtained from the proposed methodology are presented and discussed. Chapter 5, deals with concluding marks and a few recommendations for future studies and practitioners.

Chapter 2

METHODOLOGY

Tower cranes are one the most essential equipment in construction site, warehouse and etc. but tower cranes are very costly machine that consist of operators salaries, maintenance (lubricate and repairing cost), and operation cost (fuel, oil, and etc.) (Zavichi & Behzadan, 2011). Usually there is not any plan or schedule for service requests and the operator decides what to do on his/her own priority, mostly they use first-in-first-out (FIFO) pattern, which wastes time and money.

Figure 1 shows a sample of a construction site in which there are four crew and four material storage, crews are donated by C_i, where i=1,2,3,4 and material storage are donated by M_j, where j=1,2,3,4 each crew has request service from one material storage C_1 from M_3, C_2 from M_2, C_3 from M_4 and C_4 from M_1, as shown in table 2. Assume that the operator decides to deliver materials to crew number 1 first, then 2, after that 3, and the last crew will get their materials will be number 4, he/she must take materials from storage number 3, then deliver them to crew number 1, after that he/she has to take material from storage number 2, and deliver them to crew number 2, then he/she must take material from storage number 4, and transfer them to crew number 3's location, and the last group will be crew number 4, that needs their material from storage number 2, and then the hook will return to first place (crane location). In this example there are $4\, factorial\ (4 * 3 * 2 * 1)$ different alternative ways for deliver materials to each crew, as the number of crews and material storages increase, alternative ways will increase and it cause making decision getting harder and more importance. The circle in the middle shows the location of the crane.

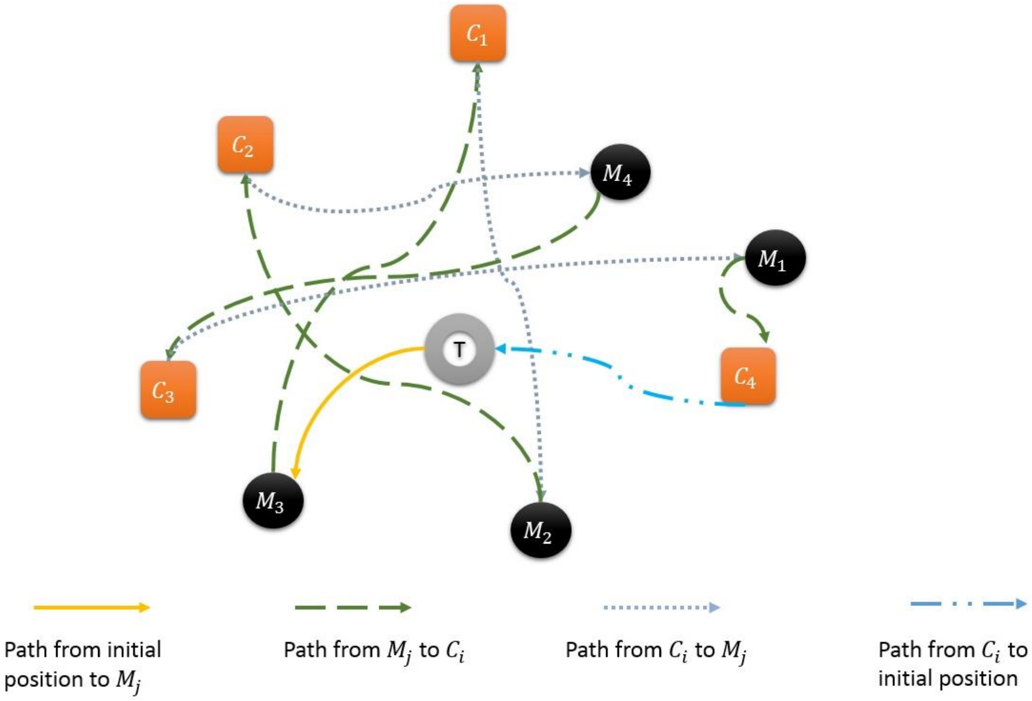

Figure 1. Example of work place

Table 2. Crews and requests

	1st	2nd	3rd	4th
Crew number	C_1	C_2	C_3	C_4
Material number	M_3	M_2	M_4	M_1

The aim of this research study is to reduce the overall cost by assigning the priority for each crew for deliver materials to them, to find a solution. The genetic algorithm method is used here to seek for the best solution. Each day operator receives a series of requests from construction teams to deliver their materials; the operator should find an appropriate service sequence.

2.1 Computing of the tower crane's hook travel time

In order to the cranes hook travel time, first of all the exact location of each crew and the material storage should be known, so the location of each crew and material storage should be specified considering X, Y and Z axis. For this aim, assumed that the location of the tower crane is at the 0 point, thus (x_T, y_T) = (0, 0), where x_T and y_T donated to tower crane position. If tower crane's hook wanted to deliver material from point A to point B with x and y coordinates of (x_A, y_A) and (x_B, y_B), then, travel time of crane's hook will be calculated with following equation:

$$T_r = \frac{\left|\sqrt{{x_B}^2 + {y_{\boldsymbol{B}}}^2} - \sqrt{{x_A}^2 + {y_{\boldsymbol{A}}}^2}\right|}{V_r} \quad (1)$$

$$T_a = \frac{\left|\tan^{-1}\left(\frac{y_B}{x_B}\right) - \tan^{-1}\left(\frac{y_A}{x_A}\right)\right|}{V_a} \quad (2)$$

$$T_h = \max\{T_r, T_a\} + \lambda . min\{T_r, T_a\} \quad (3)$$

Where T_a and T_r, donate the angular and radial travel of the tower crane. V_a and V_r , present the velocity of the crane , angular velocity of the crane's hook is addressed by V_a, and radial velocity of the tower cranes is addressed by V_r. For calculating the horizontal travel time of crane's hook T_h Eq.3 will be used. The max and min operator proposed by Zavichi et al. (2014) . For this goal, the minimum angular and radial travel time of tower crane is found and multiplied with the operator's skill internal parameter (λ),this is something like efficiency. The value in between (0-1), and then it is added with the maximum angular and radial travel time.

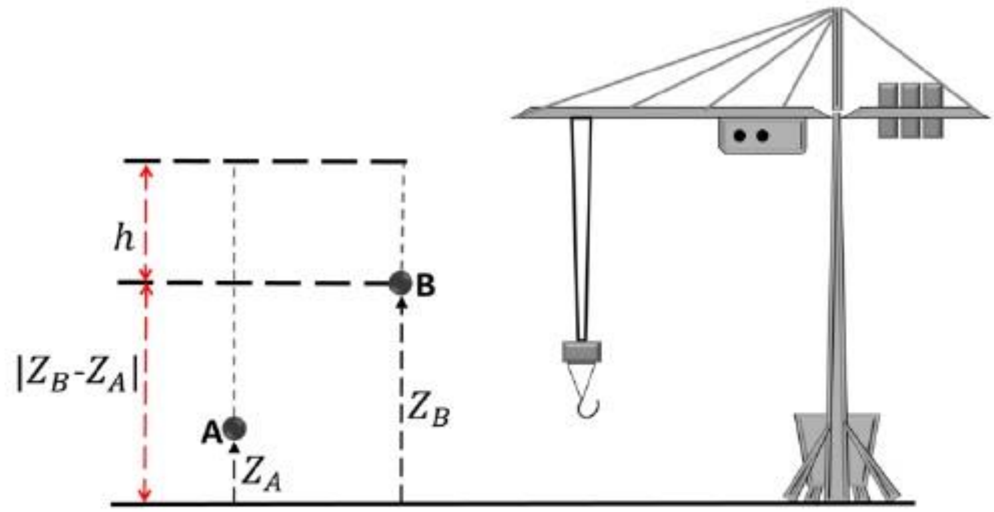

Figure 2. Elevation view of the tower crane (Zavichi et al., 2014)

Both horizontal and vertical travel time of the crane's hook should be calculated, horizontal travel time of the crane (T_h), as well as the vertical travel time of the crane (T_v). Figure 2 Shows the position of the two points A and B, Vertical travel time of the crane is the amount of time that crane spend for moving from point A to point B. In Figure 2, Z_A is the height of the point A and Z_B is the height of the point B, and V_v is vertical velocity of the crane's hook. Assume that the minimum hoisting height is h, as it is shown in Figure 2. In the equation below, the vertical velocity of the crane's hook will be gathered.

$$T_v = \frac{|Z_B - Z_A| + 2 \times h}{V_v} \tag{4}$$

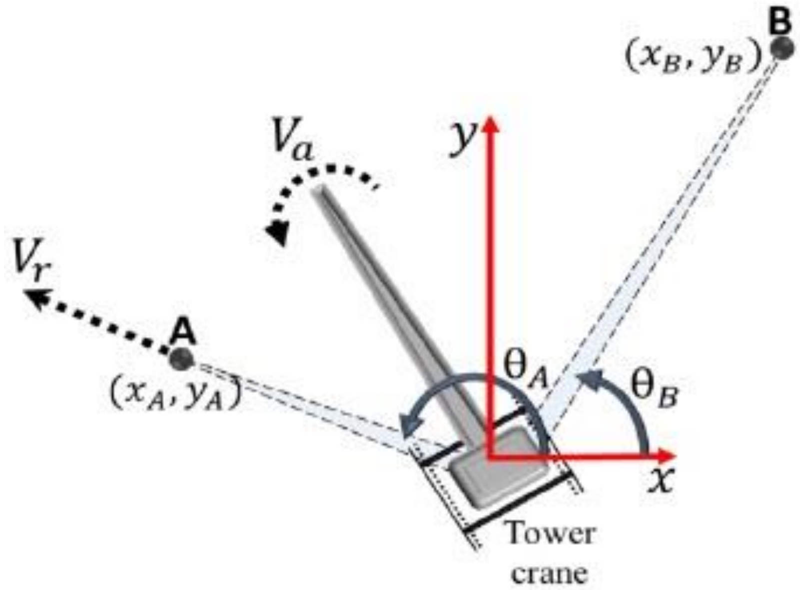

Figure 3. Plan view of the tower crane (Zavichi et al., 2014)

Based on Zavichi et al. (2014) the maximum and minimum operator, the overall time of the crane (T_T) will be calculated. For this aim, the crane operator's skill parameter (η), should be multiplied by the minimum of the crane's horizontal travel time (T_h) and crane's vertical travel time (T_v). Then it is added to the maximum of the (T_v) and (T_h). Then the summation will be multiplied by the external parameter of operator's skill (μ).

$$T_T = \mu \ . \ [max\{T_v, T_h\} + \eta . \min\{T_v, T_h\}] \quad (5)$$

2.2 Genetic algorithm

Genetic algorithm is a method of learning based on biologic improvement. This method was established by Chu and Beasley (1998). This method is addressed by evolutionary algorithms. This method is widely used when the aim is finding an optimal solutions. The basis of GA is finding the minimum answer for problems, so if the goal is finding the maximum solution it should be multiple it in (-1).

The genetic algorithm is chosen because it is appropriate when the hypothesis scape is large. Because each group has a couple of requests, hypothesis space will be 50! different alternative solution.

2.2.1 GA procedure

For solving the problem GA will produce a huge bunch of solution, every single of these solution will be evaluated by the fitness function, e.g., crane travel time and wait times. some of the best solution will be chosen and these one will produce new solutions, by this the search space will leads hypothesizes to better solution, the more is proceed the better solution will produce. This method is extremely useful if parameters chosen carefully.

2.2.2 Hypothesis space

Instead of searching in general to specific or simple to complex hypothesizes, GA will produce new hypothesizes by changing and combining the bests of hypothesizes. In each level a set of hypothesis that addressed population, will be obtained via replacing part of present population and kids.

2.2.3 Features

(1) GA can be used in such problems that has a huge searching space,

(2) It can be sued in such problems that has a complex hypothesis space,

(3) It is very useful for discrete optimizations problem,

(4) Parallelization of Genetic Programming, leads us to use cheaper computers,

(5) Since this method is used when problem has a huge hypothesis space, time is so important from the computation point of view it is expensive,

(6) Because it is a random process, there is no guarantee that optimum solution will be achieved ,

2.2.4 Usage

(1) Optimization

(2) Automatic programming

(3) Machine learning

(4) Economics

(5) Operations research

(6) Ecology

(7) Studies of evaluation and learning

(8) Social systems

2.2.5 Algorithms of genetic

The routine way of implementation of GA is as follows: at first set of population will be produced based on hypothesis. The population will be evaluated by the fitness function, then some of the best ones will be chosen and then new population will appear, some of these possible solutions (chromosomes) stay like before and the rest will be changed by genetics operators like Crossover and Mutation for producing new generation.

2.2.6 GA's parameters

A GA algorithms has these parameters:

(1) Fitness Function: a function that evaluate population.

(2) Fitness threshold: the boarder of the acceptance.

(3) P: the number of population that should be considered.

(4) R: percentage of population that will be replaced in each level via crossover.

(5) M: rate of mutation.

2.2.7 Algorithm

At first the population with P number of member an initial amount should be assigned, then for each hypothesis the function of fitness will be calculated. Then new population will produce till maximum fitness is less than the fitness threshold will be satisfied, then that hypothesizes that has the maximum number of fitness.

2.2.8 How to make a new population

GA is a population-based evolutionary algorithm where the set of solution is called the population for each generation denoted by P. At $P(1-r)$ hypothesis, where r refers to selection rate which lies in the interval of [0,1], will be selected from P number of chosen and add it to P_S, then the possibility of selecting h_i from P number of hypothesis is:

$$P\ (hi)\ =\ Fitness\ (hi)\ /\ \sum j\ Fitness\ (hj)$$

The bigger fitness hypothesis, the more possibility to be chosen. Then by the possibility that achieved from equation above $(r_p)/2$ number of hypothesis will be selected from P number of chosen solutions. The crossover rate is denoted by r_p which lies in the interval of [0,1]. The crossover operator generates two kids by the probability of r_p and they will be added to P_S.

After that m percentage of the population will be chosen and one bit of them will be reverse randomly. Then update $P_S \rightarrow$ P, and for each hypothesis in population fitness function should be calculated.

In GA hypothesis are shown as a series of bits, by doing this genetic algorithms can be applied. Phenotype is a real solution, and genotype are chromosomes that can be used for GA.

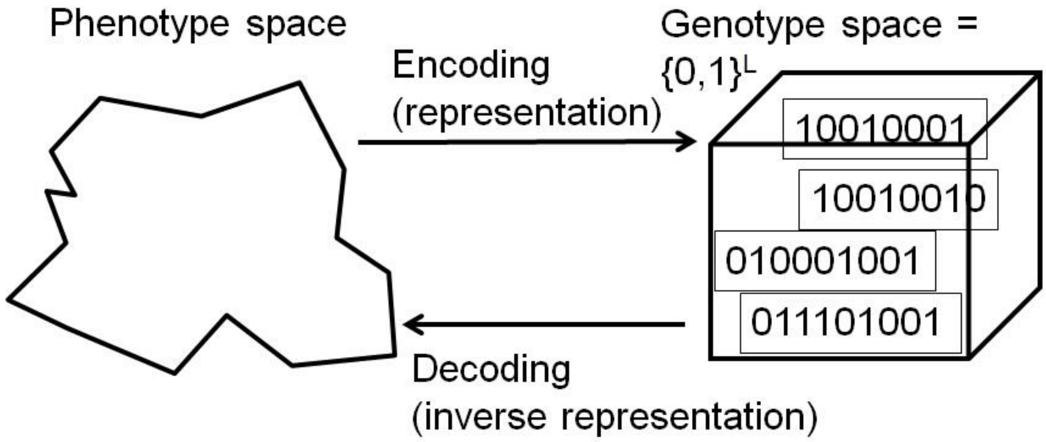

Figure 4. Converting data to readable information for applying GA (Chu & Beasley, 1998)

There is the possibility that some combinations of a few bits will produce meaningless hypothesis, for preventing this phenomenon there is 3 way: (1) use another encoding or (2) assign Genetic operators the way that discard these types and (3) assign a low amount of fitness.

2.2.9 Genetics operators

2.2.9.1 Crossover

Crossover produces two kids using two parents, for this purpose some parts of parent's bits will be copied in kids' chromosomes.

By one of these methods bits will be selected, single-point crossover, two-point crossover, and uniform crossover. For assigning place of bits that will be copied a series addressed by mask crossover will be used.

2.2.9.1.1 Single-point crossover

A point will be chosen randomly within the series, then parents will break into two parts, and each child will produce by one part of each parents.

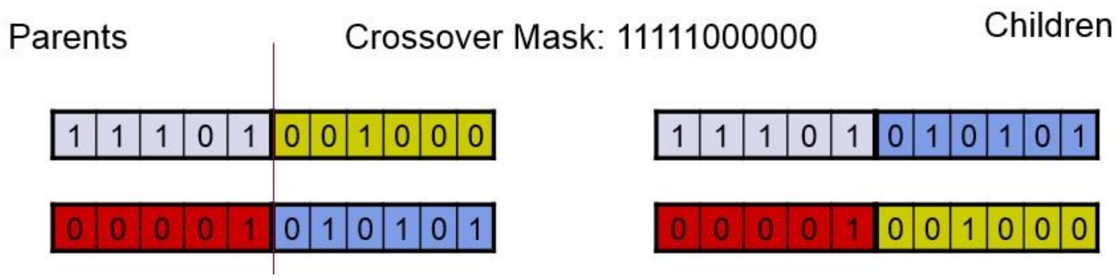

Figure 5. Example of single point cross over (Chu & Beasley, 1998)

2.2.9.1.2 Two-point crossover

Two point will be chosen randomly within the series, then parents will break into three parts, and each child will produce by one part of one parent and two part of other one.

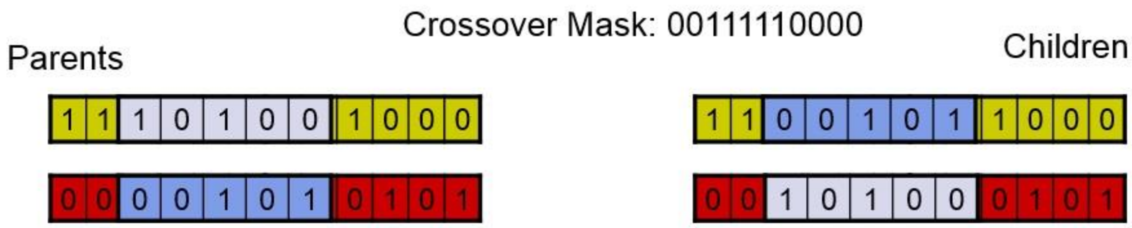

Figure 6. Example of two-point cross over (Chu & Beasley, 1998)

2.2.9.1.3 Uniform crossover

Bits will be chosen from parents uniformly.

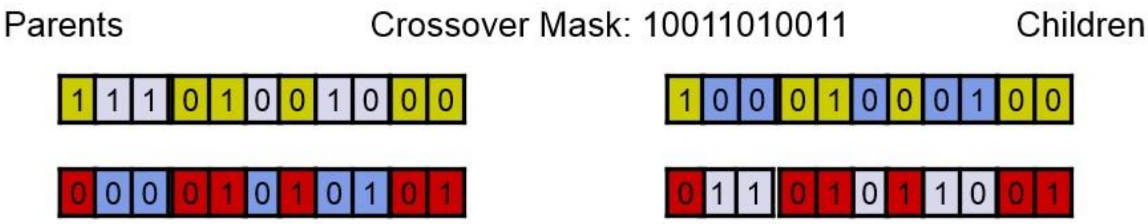

Figure 7. Example of uniform cross over (Chu & Beasley, 1998)

2.2.9.2 Mutation

Mutation operator will produce child from one parent. For this purpose, child will produce by changing just one bit of parent, this bit will be chosen randomly. Usually mutation will apply after crossover.

Figure 8. Example of mutation (Chu & Beasley, 1998)

2.2.10 Crossover or mutation

It has been years these questions are routine, which one is better? Which one is necessary? Which one is a main one?

And for the answer we can say; it depends on the problem, generally it’s better to use both of them in one question, each one has its own role, there is an algorithm that just use mutation but it’s impossible such an algorithm just use crossover.

Crossover has an explorative feature, it can explore new generation by big jumps, mutation has this feature but it’s too slow, and it will happen by accidently small change in parent. Crossover combine parent’s data, but mutation can produce new data. For achieving an optimum solution, it needs a fortune in mutation.

2.2.11 Fitness function

Fitness function is a criterion for ranking the hypothesis that helps choosing better generation for new population. Method of choosing this function is depend on the use:

Roulette wheel selection: in this method in a simple algorithm of GA possibilities of choosing a hypothesis for using in next generation is depend on ratio of its fitness to other users.

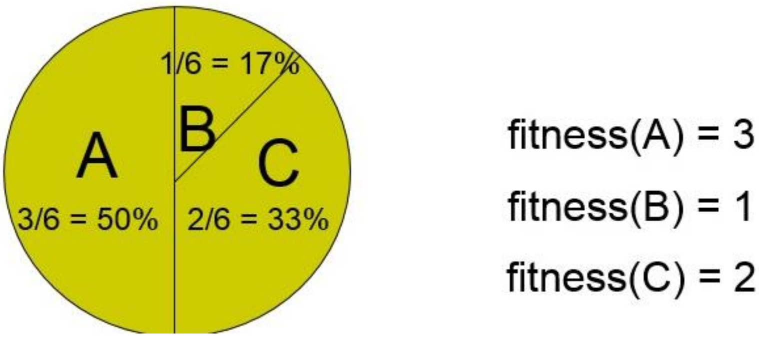

Figure 9. Roulette wheel selection method (C. Tam & Tong, 2003)

One of the problems of this method is when there are dealing with fitness that differs very much, one chromosome has big chance to be selected while others haven't too much chance.

2.2.11.1 Other methods

Elitist selection: the most appropriate member of each population will be chosen and it will be copied in new generation, then the rests are ready for process in a classical way.

Scaling selection: by increasing the average fitness of the population, weight will increase and also it will be more detailed. This method is widely used when the fitness number of the population is high and just small difference will separate them.

Tournament selection: a subset from attributes of generation will be selected and members of this generation will have a competition with others, and then just one objective of each subset will be chosen for producing.

Rank selection: every chromosome receives fitness according to the ranking that rank selection gives to them initially. The best one will have fitness N, and the worst will have fitness 1. After this process all the chromosomes will have a chance to be selected, but the problem of this method is its speed, it is slow.

2.2.12 How GA searches in the hypothesis space

Method of searching in GA is different from other methods like neural network, in neural network gradient descent constantly move from one hypothesis to other similar ones while GA can suddenly replace parent hypothesis with totally different child, so the possibility of the GA algorithm to be trapped in a local minimum or maximum is reduced, nevertheless GA is facing with crowding problem.

Crowding is a phenomenon in which user has much more compatibility than others which constantly produces similar users. In crowding similar users will take too much of the space of the hypothesis, thereby causes the speed of GA to be reduced sharply.

2.2.13 How to prevent crowding in GA

(1) Ranking: by ranking each hypothesis priority will be shown.

(2) Fitness sharing: if there are too much similar users in the population the amount of their fitness will be reduced.

2.3 Multi objective optimization

In problems where there are more than one objective, it is more difficult to seek a best solution in comparison with single objective problems. In these problem there are two or more goals which need to be simultaneously improved. For example, in a travel plan, we will consider some parameters, such as travel time, safety, comfortably and so many other factors (train station, airport, and etc.). Thus, regarding all of these conditions, it is tried to select the best travel plan which satisfies our expectation utmost.

Multi objective optimization is like a vector of variable of the objectives that leads into optimization of the vector function. These function are mathematical description of performance criteria that usually are opposed to each other. Hence, optimization means finding a solution that keeps the value of all functions. Multi objective methods are used when there are multi objective problems with several objective. Therefore there is not just one solution but a set of non-dominated solution. These group of solutions will be obtained by Pareto-optimal theory.

In this thesis, both travel time of tower crane and waiting time of each crew are important objectives and should be minimized. Based on these factors best solutions will be selected and then among these solutions, the construction manager will choose one.

Selection procedure in a multi objective problem is more complicated than single objective problems. In multi objective problems there are too many solutions which are close to each other and are called the Pareto-optimal solutions. Pareto-optimal set consists of some solutions, regarding different objectives. Almost always there is not a solution that is the best one for all the objective in the same time. For example in traveling example we cannot find the cheapest way and fastest one simultaneously, so we will consider both factors, and Pareto-optimal will represent best solutions considering all the objectives. Haider, Nadeem, and Rafiq (2014) improved the situation of one objective, the other ones will scarified, therefor it's a kind of trade-off.

2.3.1 Methods of multi-objective optimization

Method of multi objective optimization are divided into several groups based on their operation as follows:

First generation technics:

(1) Pareto

(2) Non Pareto

Second generation technics:

(3) PAES

(4) SPEA

(5) NSGA-II

(6) MOGA

(7) Micro-GA

Deb, Pratap, Agarwal, and Meyarivan (2002) presented non-dominated sorting genetic algorithm-II (NSGA-II), for producing the set of Pareto-optimal from the best solutions. The basis of the NSGA-II is choosing the best solutions within too many answers. It plots all the answers and it will choose the best ones. In multi objective problems by improving the condition of one factor we will sacrifice the other one, so usually there is not any best answer, instead of one best answer, the NSGA-II shows a number of best answers. It classify solutions which are close to each other in one Pareto-optimal.

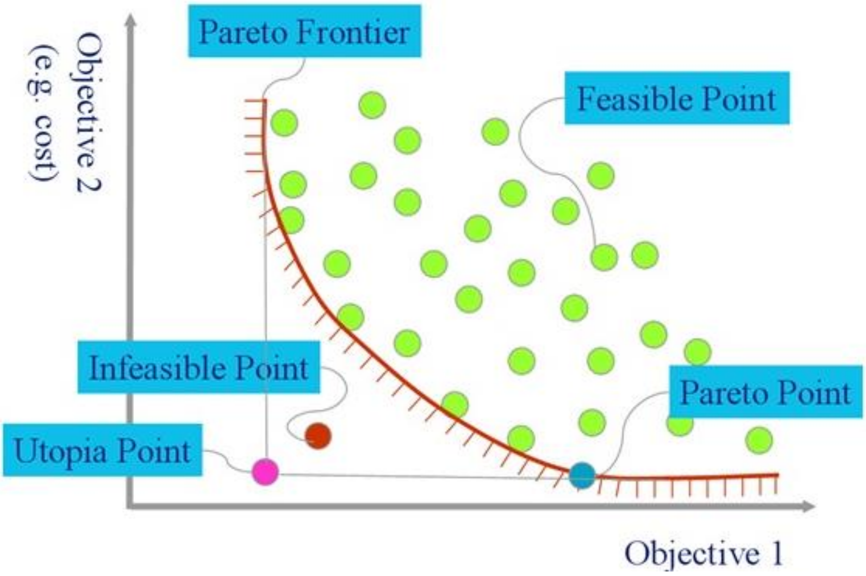

Figure 10. Typical two-objective solutions (Schaffer, 1985)

Figure 10 shows a typical two-objective optimization problem. Feasible points that they specified by green circles (ones are above the line) are the answers that they consider problem assumption and they are acceptable. Infeasible points are the one that do not follow problem assumption and they are unacceptable answers. Pareto point (blue points) is the best answers for the problem the best group of solutions are placed in Pareto frontier line.

NSGA-II has some features such as low computational requirements, simple constraint, an elitist approach and a parameter-less niching approach. Because of these features NSGA-II is widely used application in algorithms.

Chapter 3

DEFINITION OF CASE PROBLEM

3.1 Definition

In existing benchmark in the literature, that there are 50 requests for the tower cranes where the number of solutions will be $(50!)$. Enhanced tower crane operations in construction using service request optimization was coded in MATLAB R2013a. Time of processing was 12.7 minutes in average with a personal laptop (Intel® core i5-4200M CPU @ 2.50GHz with 6.00 GB RAM). Time of the processing is acceptable time considering $50!$ different scenarios in solution space, and only searching 0.0081% of the total number of potential solutions to obtain the Pareto solutions. The proposed algorithm was able to find the same Pareto solutions in 16 optimization trials out of the total 20 that were performed; this implies that the proposed approach is able to attain the same global Pareto optimal solutions with 80% accuracy. Figure 11 shows job site in our example, that is adapted from Zavichi et al. (2014).

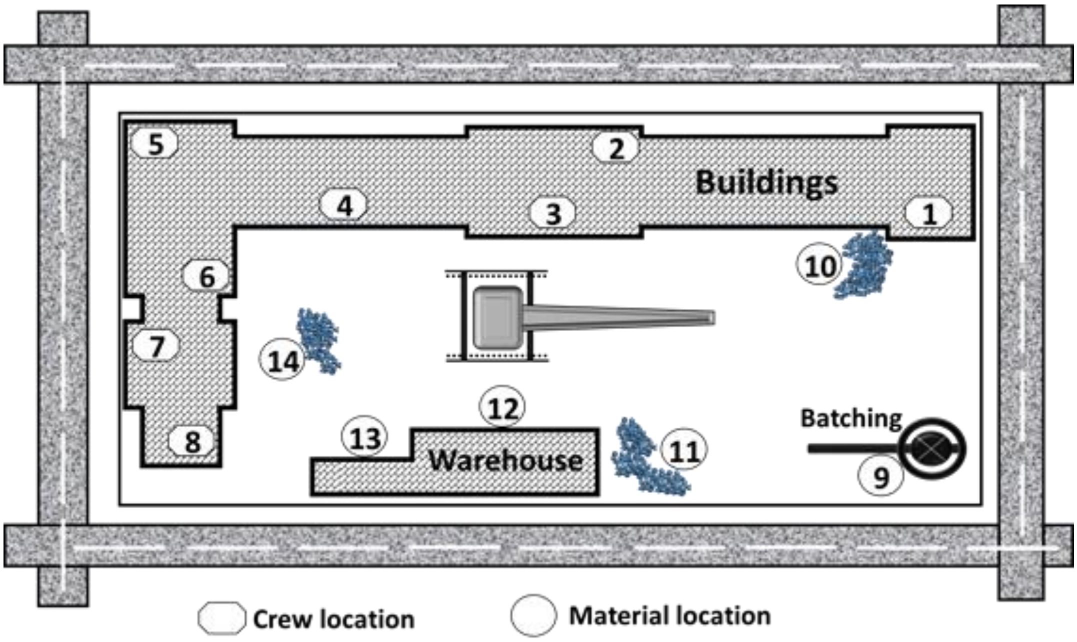

Figure 11. Case problem (Zavichi et al., 2014)

In our example there is 50 different requests, Table 3 shows a service request. In this example, the sequence of the service requests is as flows: 2nd crew has a demand from the 1st material and after that crew number 2 has requested material but this time from storage the 2nd storage, after that crew number 8 want their material from storage number 5 and so on.

Table 3. Case problem

Data																									
Request number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Material number	1	2	5	1	6	5	3	4	2	3	6	4	4	2	3	4	5	3	3	6	1	6	6	5	1
Crew number	2	2	8	1	4	2	8	6	5	4	1	6	1	1	5	1	7	7	6	2	6	5	8	6	7
Request number	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
Material number	2	3	5	1	5	1	4	3	5	5	6	6	3	5	2	1	5	4	3	6	4	4	6	5	4
Crew number	4	4	7	1	2	2	4	7	7	1	4	5	4	6	6	3	4	1	8	2	1	3	2	4	3

There are 8 crews on the jobsite and 6 material storages, each crew has several requests from crane operator, in summation there are 50 requests. Crew number 2 have 7 requests from material number 1,2,5,6 and crew number 1 have 7 requests from material number 1,4,5,6 and so on.

For delivering materials, the crane operator has 50! different sequence orders. By accomplishing one delivery request, the reaming ones should be optimized again. The best sequence of service requests is the one which minimizes the crane travel time and wait times of the construction teams to receive their materials.

Chapter 4

RESULTS AND DISCUSSION

Among 50! Possible sequences of the crane service requests, 200 solutions from the last generation in GA have been listed in Appendix A. Figure 12 shows the scatter plot for these 200 solutions where the red dots indicate the Pareto-optimal solutions. Objective 1 is standard deviation that present waiting time of the crews and objective 2 is travel time of the tower crane.

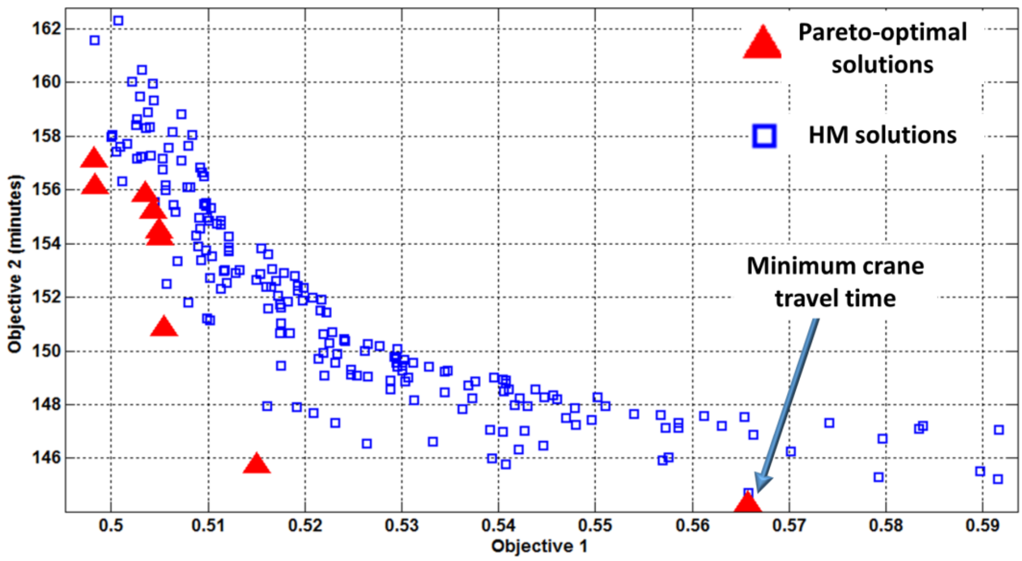

Figure 12. Final solution

This research study is a multiple-objective optimization problem. Both the crane travel time and wait time are taken into the consideration. Vertical axis shows the travel time of tower crane and the horizontal axis shows standard deviation (waiting time) of each group. The travel time of the crane is the summation of delivery time of all requests and standard deviation will be obtained from coefficient variance powered by (0.5):

$$\sigma_x = \sqrt{\sigma_x^2} \tag{6}$$

$$\sigma_x^2 = \frac{\sum (x_i - \mu_x)^2}{N} \tag{7}$$

The main goal of this research study is to reduce the travel time of crane and the standard deviation of the wait times. In Figure 12 there are best 200 possible solutions which are specified with small blue squares. Since the aim of this research study is finding the minimum of both standard deviation and travel time those ones are close to zero point are the best one. With NSGA-II application, 9 Pareto-optimal solutions are specified with red triangular icons that are called optimal crane service sequences. Within these points, the construction manager can choose which one is better for the project. If the goal was just reducing travel time of tower crane then the first red point in the right would be chosen. But according to situation of the job site, it might not be the best choice. Regarding this, if waiting cost of some group be higher than the others so construction manager will chose one solution that reduce waiting time of those crews are expensive. With this regards, the travel time of the all 9 solutions are within 145 minutes up to 154 minutes. Table 4 shows standard deviation and travel time of the 9 best solutions.

Table 4. Standard deviation and total travel time

	#	Objective 1 (Standard deviation)	Objective 2 (time, minute)
Pareto Optimal solutions	1	0.5151	145.49850
	2	0.4994	145.74254
	3	0.5076	148.71007
	4	0.5071	151.31103
	5	0.5063	151.61176
	6	0.5071	153.43597
	7	0.5477	153.66503
	8	0.4959	154.38399
	9	0.5001	154.64575

Table 4 reveals standard deviation and travel time of each solution, standard deviation present the waiting time of the crews and travel time, shows travel time of the tower crane, standard deviation should remain in a boundary.

Table 5. Travel time comparison

Travel time(min)	(1) 145.49	(2) 145.74	(3) 148.71	(4) 151.31	(5) 151.61	(6) 153.43	(7) 153.66	(8) 154.38	(9) 154.64
(1) 145.49	0	-0.25	-3.22	-5.82	-6.12	-7.49	-8.17	-8.89	-9.15
(2) 145.74	0.25	0	-2.97	-5.57	-5.87	-7.6	-7.92	-8.64	-8.9
(3) 148.71	3.22	2.97	0	-2.6	-2.9	-4.72	-4.95	-5.67	-5.93
(4) 151.31	5.82	5.57	2.6	0	-0.3	-2.03	-2.35	-3.07	-3.33
(5) 151.61	6.12	5.87	2.9	0.3	0	-1.82	-2.05	-2.77	-3.03
(6) 153.43	7.49	7.6	4.72	2.03	1.82	0	-0.23	-0.95	-1.21
(7) 153.66	8.17	7.92	4.95	2.35	2.05	0.23	0	-0.72	-0.98
(8) 154.38	8.89	8.64	5.67	3.07	2.77	0.95	0.72	0	-0.26
(9) 154.64	9.15	8.9	5.93	3.33	3.03	1.21	0.98	0.26	0

Table 5 shows differences between travel times of tower crane in 9 ultimate solutions. As it is shown, the maximum difference is 9.15 minutes so that there is not too much variation. If in a situation, the wait time of the crews are more important that travel time of tower crane construction manager can easily find the best solution.

4.1 Discussion

In this research study, the goal is to enhance the service sequence of the tower. There are 8 crew and 6 material storage on the jobsite. In total, there are 50 different requests that operator has to deliver them. Operator has 50! Different ways to deliver all the requests. By codding data in MATLAB R2013a and using Genetic Algorithm method from 50! Possible ways the best 200 ones are separated and within these 200, 9 ultimate solutions had been achieved. Since this case is two objective problem, there is not any best answer but there are small number of best ones, according the situations construction manager will decide which one should be used. In previous researches just reducing travel time of the tower crane was the aim, in figure number 12 the right, red point is the solution if just reducing travel time was the aim, regardless of waiting time of the crews. Data run for 20 times, and in 16 times the same Pareto-optimal achieved, so the solutions has 80% accuracy.

To find a solution which corresponds to the minimum travel time and standard deviation the weighted sum approach is used. However, since the travel time of the crane is of time unit it should be divided by its unit to become dimensionless. Here, the travel time of the crane is divided by its maximum value. By the time, both of the objectives are now dimensionless and the weighted sum of these objectives can be obtained. Here, the weight for the crane travel time objective is assumed to be 60%

and for the standard deviation of the wait time to be 40%. The minimum weighted sum of the objectives can be now selected as the solution which is the best.

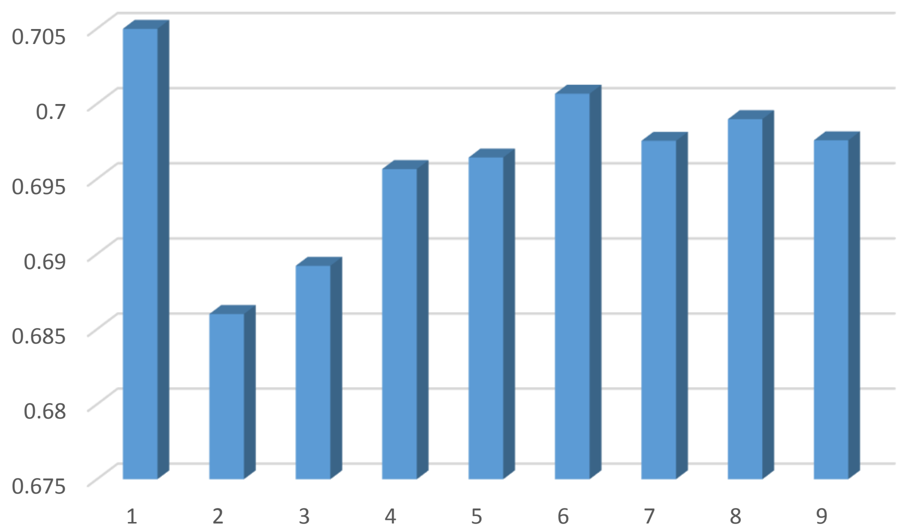

Figure 13. Ultimate solution

Figure 13 shows best solution for this scenario, when the weight of the travel time of the tower crane is 60% and weight of the waiting time of the crew's is 40%. Since the aim of this research study is minimizing both travel time of the tower crane and waiting time of each groups solution number 2 will be the best one. Travel time of tower crane is 145.74254 minutes and standard deviation is 0.51507.

As the result out of 50! different alternative ways to deliver material best 9 of them were gathered, figure 14 shows travel time of tower crane of these 9 solutions.

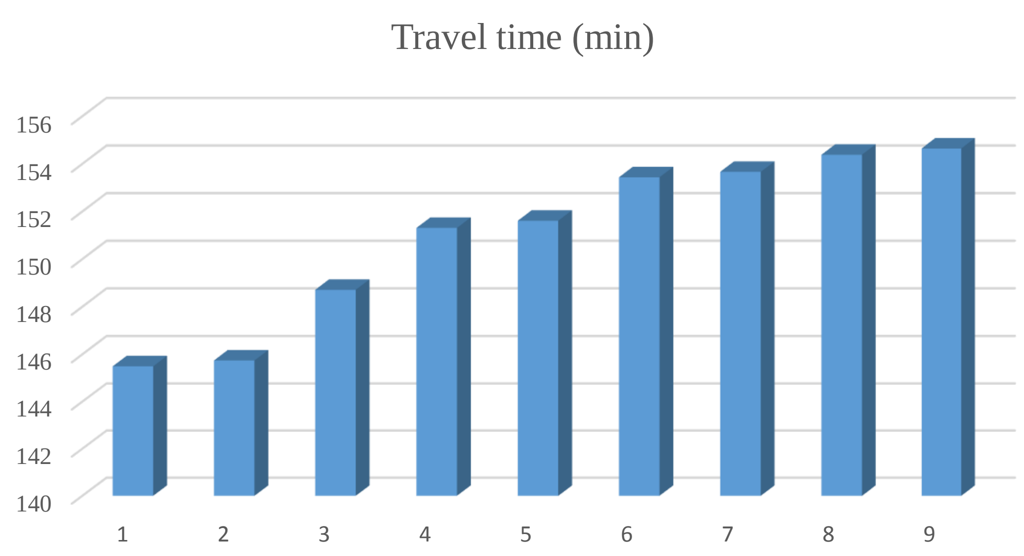

Figure 14. Travel time of tower crane

Lowest travel time of tower crane is 145 minute in this example and the greatest one is 156 minutes. The difference travel time between these 9 alternative is 11 minutes but each of them has a specific standard deviation and according to different situation every of these answers can be best one. Figure number 15 shows standard deviation of these 9 best answers.

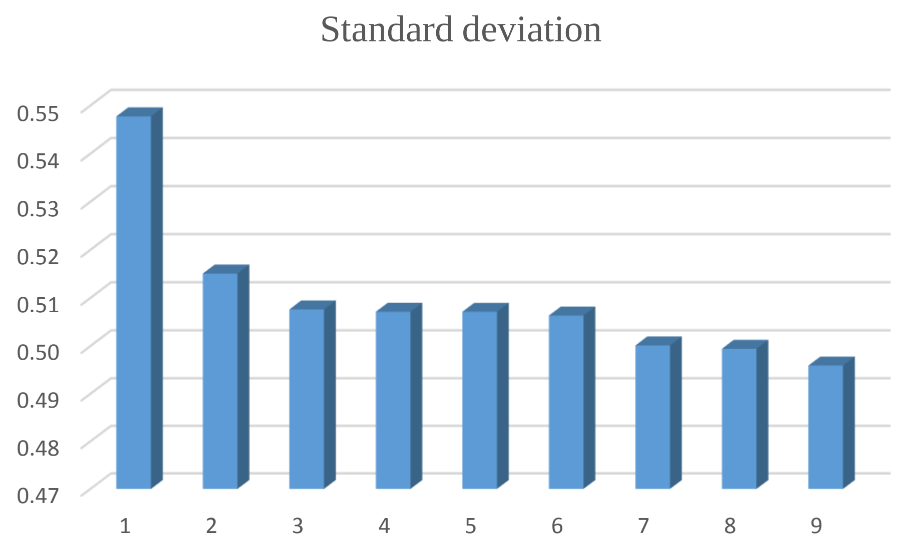

Figure 15. Standard deviation

If in some cases waiting time of one or some groups be high, construction manager by using weighted sum approach method can find best solution for every single situation.

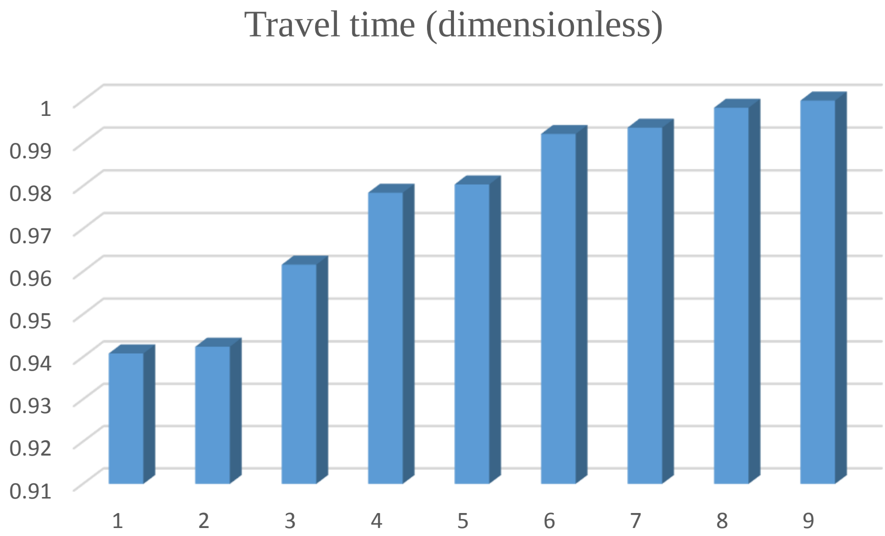

Figure 16. Travel time weight

Figure 16 is prepared for using weighted sum approach method, it shows the travel time of tower crane, since the aim is finding the minimum one. Solution 1 and 2 have a greater chance for using as an ultimate answer.

Table 6. Sequence order of service request

Pareto-optimal solutions	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	25	21	15	10	28	20	44	42	46	4	40	30	27	34	38	19	8	22	39	13	1	31	32	36	18
2	25	21	1	35	8	19	4	13	38	40	48	26	27	7	30	41	47	33	9	10	31	2	32	6	16
3	21	43	27	15	9	30	11	33	10	31	2	29	4	19	6	14	1	13	25	44	16	26	5	38	23
4	25	41	15	27	29	9	3	16	35	46	42	10	28	31	43	18	33	39	23	50	47	40	24	30	34
5	30	35	15	21	29	11	10	39	40	19	7	31	2	48	25	20	3	6	12	18	22	37	42	44	34
6	26	40	15	21	10	49	9	31	46	25	47	44	12	8	16	1	38	48	3	5	29	41	19	30	32
7	15	46	4	1	16	43	41	3	29	31	35	26	24	8	14	27	22	5	40	44	28	10	2	38	36
8	25	21	15	26	27	41	35	28	10	1	7	32	46	18	19	3	44	23	8	6	12	42	2	50	45
9	21	7	1	46	15	9	4	35	10	16	19	29	32	39	47	43	26	6	13	41	34	48	18	45	33

Sequence orders

Pareto-optimal solutions	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
1	5	48	47	49	50	17	23	12	35	29	41	45	33	37	16	14	2	26	43	9	3	7	11	6	24
2	15	12	42	3	46	29	18	23	34	17	36	5	39	22	14	44	37	24	20	49	11	28	43	50	45
3	40	48	22	45	32	24	37	12	3	42	50	35	7	28	8	39	49	36	34	20	18	46	47	41	17
4	17	49	12	45	2	13	44	36	38	5	48	14	4	21	7	32	11	8	20	37	22	6	1	19	26
5	5	17	49	27	16	4	14	28	24	50	47	26	36	46	13	9	32	38	8	45	43	41	1	23	33
6	33	18	39	24	35	36	37	23	22	34	45	28	13	14	4	17	20	6	2	50	43	7	42	11	27
7	32	7	30	25	34	17	39	12	47	19	20	18	45	21	37	6	13	33	49	23	42	48	50	11	9
8	17	36	5	37	24	48	20	34	11	40	47	31	4	16	14	38	33	49	22	29	43	9	39	30	13
9	22	11	49	50	24	42	31	44	3	5	20	40	23	8	28	37	17	27	2	38	30	14	36	25	12

Table 6 shows the sequences of 50 service request problem for the 9 Pareto-optimal solutions. The numbers in Table 6 shows the number of service requests. For example, the 1st sequence of service requests, does the 25th request first, then the 21st service request is assigned to be done. The remaining service requests are done accordingly with a similar procedure. As it shown in conclusion solution number 2 is the ultimate answer for this case study. Construction manager submit service priority number 2 to operator, it is easy for operator to follow the path. In solution number 2 operator should done service 25th request first, then the 21st service request after that 1st and so on.

According to Table 6, solution 2, operator should transfer the crane hook to the material storage 1 and from that point it takes the materials to the 7^{th} construction team who needs them. The operator will go to handle the 21^{st} service request first. Therefore, the crane hook travels from the 7^{th} construction team location to the 1^{st} material storage again and deliver the material to the 6^{th} construction team. In real practice, an electronic device can be installed inside the crane cabin to assign this sequences so that the operator can soon follow the sequence orders.

According to the Pareto-optimal service requests in Table 6, the orders in different Pareto-optimal solutions are different. Therefore, the proposed model in finding the best optimal sequence service requests can lead into various sequence orders with different objective values. However, in 1^{st}, 2^{nd}, 4^{th}, and 8^{th} the 25^{th} service request is the first request to be handled among 50 requests. The service request sequencing is a challenging issue on the construction site, especially in massive construction sites with multiple service requests. The proposed methodology is able to efficiently handle the issue within a detailed framework.

Chapter 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusions

Tower cranes are one of the most expensive equipment in the jobsite, mostly activities are related to tower crane are on the critical path, so if delay happen in these activities it cause the delay in a whole project. Reducing travel time of the tower crane and waiting time of each group will cause save a significant amount of money. Reducing travel time of the tower crane and waiting time of the crews were the aim of this research study. By using this method travel time of the tower crane will be reduced and by reducing travel time the tower crane not only the cost of operating but also the cost of maintenance will be minimize. It is obvious waiting time of the crews are different by reducing waiting time of all crews and choosing the way that minimize waiting time of costly crews project can save a significant amount of money.

Based on the results of this study, it was shown that the stability analysis to investigate the practicability of the optimized sequence of the service requests is highly beneficial. The stable optimum sequence of the crane service requests can increases the satisfaction of the construction teams from the allocation of the tower crane as it is limited and highly required for transportation and delivering the requested materials. In contrast with the optimum solution, the stable solution fairly distributes the wait times among the construction teams where in the case a construction team which is far located from the tower crane can use the tower crane without any discrimination.

The tower crane service requests as first proposed by (Zavichi & Behzadan, 2011) is a new field of tower crane operation enhancement. The application of optimization models such as GA as used in the present study, is a novel approach which is proposed to better the crane service requests. The stability analysis, measured by the standard deviation of the wait times of the construction teams, is introduced to the subject to ensure that the optimum sequence of the crane service requests is stable in a way to fairly distribute the wait times among the crew members.

Previous research in areas such as optimization of crane layout pattern and planning of physical crane motion has shown the high potential of automating crane operations in improving productivity and decreasing the overall project cost. This is mainly due to the fact that cranes are often the most expensive pieces of equipment in construction and manufacturing and activities that rely on crane service mostly fall on the project critical path. Despite previous work in this field, crane operators still rely on their visual assessment and personal judgment of jobsite conditions and ongoing activities to decide when and in what order crane service requests are fulfilled. This subjective and often imprecise decision-making can lead to work delays and may even affect the project time and cost in long term. In this research, an innovative optimization method was developed which takes advantage of modified LP and is derived from the original TSP with DFJ formulation and sub-tour elimination. This method will serve as the backbone of an automated decision support system that assists crane operators in prioritizing outstanding crane service requests based on locations of crews and material, as well as the latest position of the crane hook. A sample crane operations case was also presented and solved using the presented method.

The small run time of the optimization model makes it useful in practice, helping reduce crane operation time and crane-related activity costs considerably. The developed model optimizes the crane travel time only, which is a significant portion of crane cycle operations, especially in high rise constructions where the loading and unloading times constitute a small portion of the crane movement cycle.

Similar to any other modelling study, this study had some limitations and simplifying assumptions. Here, the travel time between two nodes was considered to be deterministic while the travel time can vary in practice. Future studies can consider stochastic travel times. Given that the time savings increase with an increased travel time resulting from elevation differences, future studies can investigate the effects of larger elevation differences (more than 10 m) on the travel time. This study assumed that each loaded bucket can be sent to one target location only, i.e., the crane hook does not visit multiple demand nodes after being loaded. Future studies might relax this assumption. To make the developed proof-of-concept model more practical, task deadline, sequence priority, and intermittent requests can be added to the problem formulation. While in this study the travel time was assumed to be independent of the load, future studies can evaluate the effects of material weight on the travel time. Finally, given the crane operation efficiency is strongly tied to the project duration and cost, future studies might consider evaluating this connection.

5.2 Recommendations

As the results revealed, the author recommends that crane service request done by computer-aided procedure can enhance the quality of sequencing the crane service requests. More time-saving and satisfaction of the construction teams can be obtained. The present study can be extended to be applied in real practice, for example by devising a device to be installed in the tower cranes' cabin in order to aid the crane operator to sequence the request services more efficiently. It can be recommended that the project manager collects the service requests on a daily basis, so as to pre-schedule the crane service requests.

It is recommended that the velocity of the tower crane to be considered by its uncertainty through using fuzzy set theory. Based on the technical efficiency of the tower crane, the velocity of the tower crane can be expressed through fuzzy number with either triangular or trapezoidal membership functions. As future directions based on this thesis, it is recommended to take into account the load type i.e., heavy equipment, material, or etc. which can affect the efficiency of the tower crane. As it is obvious, the type of material to be transported affects the velocity of the tower crane hook so as the travel time of the crane can be affected. In other cases when the material volume is greater than the capacity of the crane bucket, there is the need for the crane to travel back and forth several of times. It is believed by the authors that if the assumptions are modified according to the real practice, the flexibility of the crane service request optimization models can be improved significantly.

In another aspect, some technological devices can be devised with more user-friendly interface through which the crane operator can enhance and improve his/her decisions to fulfil the service requests. With this respect, a device which can collect the service requests from the crew members on a daily basis can be linked with the optimization model proposed here so as to be installed in the tower crane in order to aid the crane operator to manage the service requests more efficiently.

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APPENDICES

Appendix A: The population in the last generation of GA

#	Standard Deviation	Crane travel time (min)
1	0.51506792	145.7425397
2	0.499420911	154.3839899
3	0.507613401	148.7100683
4	0.507120787	151.6117648
5	0.506330594	153.4359669
6	0.50713035	151.3110328
7	0.547742716	145.4985017
8	0.495944273	154.6457512
9	0.500118815	153.6650261
10	0.503217712	154.0637302
11	0.506945625	154.0437246
12	0.507338617	153.060879
13	0.501150411	156.2836133
14	0.522721159	147.8662533
15	0.519662259	149.5479251
16	0.520322353	148.8884524
17	0.510438177	151.9403796
18	0.503025834	155.5638507
19	0.507875292	152.2613233
20	0.551999657	145.9433354
21	0.584554487	145.8256915
22	0.517142029	149.9151708
23	0.521560995	148.6150034
24	0.519788477	149.4160654
25	0.541962882	146.0360025
26	0.516061322	150.5185479
27	0.537576046	146.088748
28	0.587086638	145.654298
29	0.498824418	157.546829
30	0.516512867	150.1176033
31	0.524899655	147.3560212
32	0.498412403	157.5959089
33	0.512399573	150.9523207
34	0.500558784	157.8515209
35	0.504916379	154.4442288
36	0.548139073	146.6658781
37	0.543823497	147.0227178
38	0.546223971	147.0063006
39	0.511921758	152.52467
40	0.511450595	153.0523043
41	0.511614126	152.5351479
42	0.512842958	152.1160207
43	0.512785626	152.2304767
44	0.509364615	153.2701504

#	Standard Deviation	Crane travel time (min)
45	0.501598447	157.2521718
46	0.524983494	149.5122543
47	0.502105179	156.3937893
48	0.5220232	149.8280408
49	0.52513951	147.9167681
50	0.557472017	146.3269058
51	0.592071976	146.3200815
52	0.521856808	149.9975499
53	0.524532159	149.6333999
54	0.525017395	149.2681057
55	0.516878646	150.6978498
56	0.503962444	154.4982935
57	0.505877784	154.1319561
58	0.514497956	151.1842534
59	0.512597174	152.4256547
60	0.518625111	150.1707971
61	0.516309651	151.6623406
62	0.506577592	154.1939513
63	0.506515725	154.2536101
64	0.504019531	155.5383553
65	0.504020673	155.3318394
66	0.518199925	151.207917
67	0.518473323	150.7801648
68	0.500817772	162.2723478
69	0.501574425	159.8993783
70	0.56898704	146.5495391
71	0.59503279	146.466176
72	0.574776319	146.5266904
73	0.534685567	148.6292866
74	0.532507294	148.9260621
75	0.543211582	147.9218658
76	0.529967172	149.122328
77	0.53864923	148.4273753
78	0.542290983	148.2798849
79	0.549384607	147.1658899
80	0.547362655	147.1925638
81	0.525325313	150.3983056
82	0.503542571	158.6925332
83	0.503660482	157.3859992
84	0.509790595	153.7412834
85	0.510170593	153.5463905
86	0.511725427	152.9773653
87	0.514526835	152.9120615
88	0.522264677	150.6245305

#	Standard Deviation	Crane travel time (min)
89	0.525426085	149.956391
90	0.560151704	146.5857148
91	0.511154663	153.3890542
92	0.515819018	152.1245977
93	0.52731816	149.4132875
94	0.514888017	152.6261707
95	0.510749894	153.4284305
96	0.525639831	149.5090209
97	0.553372089	146.8905917
98	0.572113996	146.5414479
99	0.504991343	154.7818908
100	0.516829183	152.0798365
101	0.517942953	151.774574
102	0.506719242	155.1702544
103	0.507949999	154.2162672
104	0.504245758	155.8246811
105	0.506296606	155.3378017
106	0.521313968	150.9023687
107	0.521831565	150.8431865
108	0.519297467	151.1632018
109	0.520408321	151.1324168
110	0.518650462	151.6882125
111	0.519134379	151.5109148
112	0.502638528	160.0100974
113	0.515122443	152.814913
114	0.528753304	149.4374726
115	0.516816719	152.4615212
116	0.573180055	146.8173977
117	0.527526124	150.1271575
118	0.541909894	148.5955065
119	0.546135922	148.3783284
120	0.532587024	148.9891362
121	0.539631877	148.732148
122	0.540581609	148.6635997
123	0.547624144	148.2596915
124	0.551215911	147.4620234
125	0.525803297	150.6302292
126	0.525882845	150.4108184
127	0.510907368	153.8716379
128	0.512622002	153.4427825
129	0.511952904	153.5716203
130	0.514817801	153.1453884
131	0.547846945	147.6646679
132	0.564972571	146.8489815

#	Standard Deviation	Crane travel time (min)
133	0.528533982	149.8067972
134	0.503782304	158.7172123
135	0.525353116	150.8366408
136	0.504526122	155.5533845
137	0.504637243	155.6803272
138	0.516912943	152.4524499
139	0.517108216	152.2718552
140	0.508558387	154.605071
141	0.506939805	155.2504484
142	0.510301274	154.4991522
143	0.509913705	154.5788677
144	0.50434754	159.2616598
145	0.522245906	150.8996691
146	0.520501654	152.0184416
147	0.519128877	152.1291149
148	0.522837438	150.870046
149	0.520788351	151.2512196
150	0.567748624	147.0266421
151	0.548068162	147.9001976
152	0.54840898	147.8898891
153	0.503046203	160.5461086
154	0.516586318	153.1399264
155	0.530449567	149.4765514
156	0.529615279	149.9837376
157	0.530489552	149.4454918
158	0.530214126	149.5388992
159	0.576504983	146.8866759
160	0.529071743	150.1756887
161	0.543933893	148.6051956
162	0.543060015	148.6100357
163	0.54101721	148.7050566
164	0.5331099	149.1657262
165	0.514855059	153.1836228
166	0.511476603	154.3668123
167	0.528349905	150.6692688
168	0.534134941	148.9908967
169	0.528758286	150.3644881
170	0.513529994	153.6285226
171	0.5417178	148.6895464
172	0.539729508	148.9517288
173	0.555096133	147.6323434
174	0.528250553	150.6823714
175	0.56648982	147.1582389
176	0.513014001	154.2952479

#	Standard Deviation	Crane travel time (min)
177	0.55682214	147.5256862
178	0.547778875	148.395223
179	0.504504006	155.8931583
180	0.527367263	150.7883801
181	0.565173906	147.1962835
182	0.504978936	155.6987026
183	0.517045469	152.5286593
184	0.517471797	152.343971
185	0.504528044	156.9526353
186	0.557948901	147.5906364
187	0.509746992	154.7185881
188	0.508965168	155.0022328
189	0.508029252	155.4890247
190	0.520882097	151.4715686
191	0.521671291	151.4289452
192	0.527632794	150.9588761
193	0.519202976	152.221767
194	0.568044053	147.3412829
195	0.568817774	147.200614
196	0.569077564	147.1532009
197	0.549641314	147.9649849
198	0.548834973	148.2011767
199	0.557786264	147.7689701
200	0.531164903	149.7500301