OPTIMISATION OF TOWER CRANE USAGE IN PLANNING OF PRECAST CONSTRUCTION PROJECTS

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TABLE OF CONTENTS

Topic:

ACKNOWLEDGEMENT i
TABLE OF CONTENTS iii
SUMMARY vi
NOMENCLATURE vii
NOTATIONS viii
ABBREVIATIONS x
LIST OF FIGURES xi
LIST OF TABLES xvi

Chapter I: Introduction

1.1 Background Information 1
1.1.1 The Usage of Cranes in the Construction Industry 1
1.1.2 Optimisation of the Usage of Cranes 2
1.2 Objective and Rationale of the Study 3
1.3 Methodology of the Study 4
1.4 Scope and Limitation of the Present Study 5
1.5 Organisation of the Thesis 5

Chapter II: Literature Review

2.1 Approaches for Optimising Crane Usage in Construction Industry 7
2.2 Crane Location Problem 8
2.3 Summary of Literature Review 15

Chapter III: Crane Location Problem (CLP)

3.1 Discussion about CLP 17
3.1.1 Possible Locations of Tower Crane ....
3.1.1.1 Site Area and Its Constraints 17
3.1.1.2 Coverage Requirement 18
3.1.1.3 The Building and Its Components 19
3.1.1.4 The Cranes and Their Operational Factors ....
3.1.1.5 Statutory Regulations 20
3.1.1.6 Locations for a Group of Tower Cranes 21
3.1.1.7 Summary about Tower Crane Locations 21
3.1.2 Supply Point Locations of Tower Crane 22
3.1.3 Lifted Assignment Policies 23
3.1.4 Lift Sequence – Installation Order 24
3.1.4.1 Installation according to Batches ....
3.1.4.2 Installations of Small Groups in the Same Batch 25
3.1.5 Safety Aspect – Control of Tower Crane Collisions 26
3.1.5.1 Classification of Collisions between Tower Cranes 27
3.1.5.2 Previous Approaches to Control Collisions between Tower Cranes ....

3.1.5.3 Control the Collisions between Two (Saddle-Jib) Tower Cranes 30
3.2 Overview of the Proposed Program for CLP 35
3.2.1 Pre-Process Algorithms Module (PPAM) 36
3.2.1.1 Define Possible Locations of Tower Crane – Generation Module I............. 38
3.2.1.2 Define Possible Supply Point – Generation Module II................................ 39
3.2.1.3 Task Grouping and the Installation Priority... 40
3.2.1.4 Database and How to Handle Data ....
3.2.2 Optimization Module (OM)... 41
3.3 Computer Model for CLP ....
3.3.1 Objective and Scope of the Model for CLP..
3.3.2 Expected Outcome of the Model 42
3.4 What Makes the CLP Hard? 43
3.4.1 Scaling Issues - The Size of the Problem...
3.4.2 Uncertainty and the Dynamic Nature of Real Problems................................ 45
3.4.3 Infeasibility - Sparseness of the Solution Space 46
3.5 Assumptions of the Model 48

Chapter IV: Implementation of GA for CLP

4.1 The Rationale of Using GA for CLP 49
4.2 Implementation of the GA Model for CLP... 50
4.2.1 Encoding of a Chromosome – Representation Scheme ....
4.2.1.1 Crane Location Genes (CLG) 51
4.2.1.2 Supply Point Genes (SPG)... 52
4.2.1.3 Crane Assignment Genes (CAG)...
4.2.1.4 Crane Database Genes (CDG) 53
4.2.1.5 The Overall Chromosome of CLP ....
4.2.1.6 Problems of the Binary String Representation and Solutions..................... 54
4.2.2 Building the Objective Function of CLP 55
4.2.2.1 Model to Calculate Hoisting Time of a Single Lift ....
4.2.2.2 Calculate Hoisting Time of a Group of Tasks According to Batches......... 57
4.2.2.3 Final Objective Function.. 59
4.2.3 Constraints and How to Handle Constraints of CLP 60
4.2.3.1 Constraints Group 1 – Producing a Valid Chromosome ....
4.2.3.2 Constraints Group 2 – Operational Constraints 61
4.2.4 Customized the GA Operators 63
4.2.4.1 Combinational Initialiser (Initialising Operator) 64
4.2.4.2 Combinational Permutation (Combinational Swap Mutation) 67
4.2.4.3 Combinational Crossover (1 Point Crossover and OPMX)......................... 70
4.2.5 Outline of the GA Process for CLP 72
4.2.6 Optimize the GA Parameters for CLP ....
4.2.6.1 Population Size: Test –Discussion – Recommendation for CLP................ 73
4.2.6.2 Mutation rate: Test – Discussion – Recommendations for CLP................. 79
4.2.6.3 Crossover rate: Test – Discussion – Recommendations for CLP 86
4.2.6.4 Recommended GA Parameters for CLP 93
4.3 Strategy of Running the GA Model for CLP 93

Chapter V: Applications of GA Model for CLP

5.1 Practical Applications of GA Model for CLP.. 95

5.1.1 Checking the Crane Capacity (R & Q) – Selection of the Tower Crane Models
5.1.2 Testing the Symmetric Layout 106
5.1.3 Testing the Interaction between the Supply Point Locations and the Crane Locations 113
5.1.4 Selection of the Crane Locations 114
5.1.5 Selection of the Supply Points 115
5.1.6 Crane Assignment Policy – Balancing the Crane's Work ....
5.1.7 Deciding the Number of Cranes 115
5.1.8 Refinement of the Lift Sequence - Crane Scheduling 118
5.1.9 Pre-caster Delivered Plan 118
5.1.10 Further Development – Checking the Supply Point Capacity 119
5.2 Practical Application – A Case Study in PUNGGOL Site ....
5.2.1 Project Information 119
5.2.2 Implementation of the GA Model – Data Preparations 121
5.2.2.1 Block 636A & 636B – Single Tower Crane 122
5.2.2.2 Block 635A, 635B & 635C – Multiple Tower Cranes 127
5.2.3 Results 133
5.2.3.1 Block 636A & 636B – Single Tower Crane 133
5.2.3.2 Block 635A, 635B & 635C – Multiple Tower Cranes 135

Chapter VI: Conclusions, Assessments and Recommendations for Further Study

6.1 Conclusions 142
6.2 Assessments 142
6.3 Recommendations for Further Study – Improvements 144

REFERENCE / BIBLIOGRAPHY 146

APPENDIX A: Pseudo-Code for the Customised Genetic Operators

A.1 Customised Initialiser 157
A.2 Customised Combinational Mutation 158
A.3 Customised Combinational Crossover 160
A.4 Sample Code of the Greedy Algorithm to Assign Initial Value for CLG .. 161

APPENDIX B: PUNNGOL Site – the Poh Lian Project

B.1 Project Information 162
B.2 Summary Data – Block 636A and 636B ....
B.2.1 Supply Point Locations' Coordinates 162
B.2.2 Crane Locations' Coordinates 163
B.2.3 Crane Database ....
B.2.4 Number of Lifted Modules in each Small Group ($N_{ingroup}$) 163
B.2.5 Lift priority of each small group 164
B.2.6 Installation Locations of Precast Elements 164

SUMMARY

In high-rise construction, whether using cast in-situ or precast concrete, the vertical material transportation is of paramount importance and the majority of lifting operations is carried out using tower cranes. Therefore, the tower crane and its supply point locations become the key components of the temporary site layout facilities for high-rise construction projects. Optimization of the locations of the tower cranes and their supply points is then the most important part of facilities layout planning, which is also the central focus of this study. The optimization of tower crane locations depends on many factors that influence the feasibility and safety of crane work during the installation, including the site constraints, the shape and size of the building, the size and weight of precast units, the crane configurations, the crane market, the statutory regulations, etc. These factors vary from one project to another, resulting in different site layout strategies and approaches. This fact makes the crane location problem (CLP), which is recognized as a nonlinear and discrete system optimization problem, difficult to solve and in fact, the CLP remains to be solved by trial and error method with little reference.

A computer program, using genetic algorithm (GA), has been developed by the author to assist in the selection and positioning of tower crane(s) on the construction site with quantitative evaluations of its (their) total hoisting time. The program takes into account the effects of the safe installation order (the lifting sequence), the balance movements of tower crane, the various configurations of different tower crane models available to choose from, and the interdependent relation between tower crane locations and supply point locations. These mentioned features make the program more practical and relevant to real site practices. In fact, it has been the first program developed to solve the CLP for the high-rise precast construction projects. The program is also the only program that is capable of dealing with multiple tower cranes and multiple supply points at the same time.

NOMENCLATURE

Cranes, Construction, Hoisting Time, Lifting, Project Management, Planning, Optimising, NP-hard Problem, Genetic Algorithm (GA), Site Layout Facility.

LIST OF TABLES

Table 4.1 Recommended GA Parameters

Table 4.2 Default Parameters for CLP

Table 5.1 Summary Results of the Crane Capacity Test in Scenarios 1 to 4

Table 5.2 Summary Results of Two Symmetric Solutions – Scenario 1

Table 5.3 Summary Results of Two Symmetric Solutions – Scenario 3

Table 5.4 The Changes of Supply Points and Lift Sequence in Scenario 1 to Scenario 3 of Symmetric Test Series Due to the Change of Tower Crane Layout

Table 5.5 Results of the Number of Crane Tests

Table 5.6 Summary of Project Information

Table 5.7 Possible Tower Crane Locations – Block 636A & 636B – PUNGGOL Site

Table 5.8 Possible Supply Point Locations – Block 636A & 636B – PUNGGOL Site

Table 5.9 Possible Tower Crane Locations – Block 635A, B & C – PUNGGOL Site

Table 5.10 Possible Supply Point Locations – Block 635A, B & C – PUNGGOL Site

Table 5.11 Lifted Assignments of Groups of Precast Components to Supply Points

Table 5.12 Assignment Policies for Groups of Precast Components - Optimised Solution

Table 5.13 Assignment Policies for Groups of Precast Components – On Site Solution

Table B.1 Installation Locations of Precast Elements

LIST OF FIGURES

Figure 3.1 Lifting Sequence in a Small Group

Figure 3.2 Severity of Conflicts

Figure 3.3 Control Collisions by (a) Using Switches & (b) Levelling Jibs at Different Heights

Figure 3.4 Possible Indirect Collision Recognition: (a) No Collision (b) Possible Collision

Figure 3.5 The Overlap Time

Figure 3.6 The Working Zone and Overlap Area of Crane m (The Higher Crane)

Figure 3.7 The Working Zone and Overlap Area of Crane n (The Lower Crane)

Figure 3.8 Flowchart of I-Lift Program for CLP

Figure 3.9 Flowchart of Pre-Process Algorithms Module (PPAM)

Figure 3.10 Flowchart of Generation Module I – Possible Crane Locations

Figure 3.11 Flowchart of Generation Module II – Possible Supply Point Locations

Figure 3.12 Flowchart of Generation Module III - Task Grouping & Installation Priority

Figure 3.13 Solution Space: Feasible Area and Infeasible Area

Figure 4.1 General Structure of the CLP Chromosome

Figure 4.2 Model to Compute the Hook Travel Time

Figure 4.3 Illustration of Calculating the Crane Hoisting Time according to Batches

Figure 4.4 Detail Process of Evaluating the Fitness Value with Operational Constraints

Figure 4.5 Randomly Generated Values for Group of Genes in Chromosome

Figure 4.6 Problem of Simple Initialiser in CLG and CDG

Figure 4.7 Initialiser Applied for Groups of SPG and CAG with a Temporary Array

Figure 4.8 Mechanism of the Greedy Algorithm

Figure 4.9 Initialiser Applied for Groups of CLG and CDG with a Temporary Array

Figure 4.10 Permutation Takes Place in a Group of Genes

Figure 4.11 Problem of the Simple Mutation in CLG and CDG

Figure 4.12 Permutation Applies for Groups of CLG and CDG

Figure 4.13 Permutation Applies for Groups of CLG and CDG with Temporary Array

Figure 4.14 OPMX for CLG and CDG of CLP

Figure 4.15 Flowchart of the GA Model of CLP

Figure 4.16 Tower Crane Layout – Crane Capacity Test Scenarios

Figure 4.17 GA Performance in 5 Independent Runs of Crane Capacity Test – Scenario 1, N_{pop} = 5

Figure 4.18 GA Performance in 5 Independent Runs of Crane Capacity Tests – Scenario 1, N_{pop} = 10

Figure 4.19 GA Performance in 5 Independent Runs of Crane Capacity Tests – Scenario 1, N_{pop} = 20

Figure 4.20 GA Performance in 5 Independent Runs of Crane Capacity Tests – Scenario 4, N_{pop} = 5

Figure 4.21 GA Performance in 5 Independent Runs of Crane Capacity Tests – Scenario 4, N_{pop} = 10

Figure 4.22 GA Performance in 5 Independent Runs of Crane Capacity Tests – Scenario 4, N_{pop} = 20

Figure 4.23 GA Performance in 10 Independent Runs of Symmetric Test 1 – Scenario 5, P_{mut} = 0.5

Figure 4.24 GA Performance in 10 Independent Runs of Symmetric Test 1 – Scenario 5, P_{mut} = 0.1

Figure 4.25 GA Performance in 10 Independent Runs of Symmetric Test 2 – Scenario 3, P_{mut} = 0.5

Figure 4.26 GA Performance in 10 Independent Runs of Symmetric Test 2 – Scenario 3, P_{mut} = 0.1

Figure 4.27 GA Performance in 10 Independent Runs of Number of Crane Test 3 – Scenario 1 (N_{crane} = 1), P_{mut} = 0.1

Figure 4.28 GA Performance in 10 Independent Runs of Number of Crane Test 3 – Scenario 1 (N_{crane} = 1), P_{mut} = 0.01

Figure 4.29 GA Performance in 10 Independent Runs of Number of Crane Test 3 – Scenario 2 (N_{crane} = 2), P_{mut} = 0.1

Figure 4.30 GA Performance in 10 Independent Runs of Number of Crane Test 3 – Scenario 2 (N_{crane} = 2), P_{mut} = 0.01

Figure 4.31 GA Performance in 10 Independent Runs of Number of Crane Test 3 – Scenario 3 (N_{crane} = 3), P_{mut} = 0.1

Figure 4.32 GA Performance in 10 Independent Runs of Number of Crane Test 3 – Scenario 3 (N_{crane} = 3), P_{mut} = 0.01

Figure 4.33 GA Performance in 10 Independent Runs of Number of Crane Test 1– Scenario 1 (N_{crane} = 1), P_x = 0.6

Figure 4.34 GA Performance in 10 Independent Runs of Number of Crane Test 1– Scenario 1 (N_{crane} = 1), P_x = 0.9

Figure 4.35 GA Performance in 10 Independent Runs of Number of Crane Test 1– Scenario 2 (N_{crane} = 2), P_x = 0.6

Figure 4.36 GA Performance in 10 Independent Runs of Number of Crane Test 1– Scenario 2 (N_{crane} = 2), P_x = 0.9

Figure 4.37 GA Performance in 10 Independent Runs of Number of Crane Test 1– Scenario 3 (N_{crane} = 3), P_x = 0.6

Figure 4.38 GA Performance in 10 Independent Runs of Number of Crane Test 1– Scenario 3 (N_{crane} = 3), P_x = 0.9

Figure 4.39 GA Performance in 10 Independent Runs of Number of Crane Test 2– Scenario 1 (N_{crane} = 1), P_x = 0.6

Figure 4.40 GA Performance in 10 Independent Runs of Number of Crane Test 2– Scenario 1 (N_{crane} = 1), P_x = 0.9

Figure 4.41 GA Performance in 10 Independent Runs of Number of Crane Test 2– Scenario 2 (N_{crane} = 2), P_x = 0.6

Figure 4.42 GA Performance in 10 Independent Runs of Number of Crane Test 2– Scenario 2 (N_{crane} = 2), P_x = 0.9

Figure 4.43 GA Performance in 10 Independent Runs of Number of Crane Test 2– Scenario 3 (N_{crane} = 3), P_x = 0.6

Figure 4.44 GA Performance in 10 Independent Runs of Number of Crane Test 2– Scenario 3 (N_{crane} = 3), P_x = 0.9

Figure 4.45 Illustration of Three Termination Criteria for the GA Model.

Figure 5.1 The Tower Crane Layout – Crane Capacity Tests

Figure 5.2 Load Radius Curve – Crane Capacity

Figure 5.3 Results of the Optimized Tower Crane Layout – Scenario 1, Crane Capacity Tests

Figure 5.4 Results of the Optimized Tower Crane Layout – Scenario 2, Crane Capacity Tests

Figure 5.5 Results of the Optimized Tower Crane Layout – Scenario 3, Crane Capacity Tests

Figure 5.6 Results of the Optimized Tower Crane Layout – Scenario 4, Crane Capacity Tests

Figure 5.7 Checking for the Tower Crane Capacity – Scenario 1, Crane Capacity Tests

Figure 5.8 Checking for the Tower Crane Capacity – Scenario 2, Crane Capacity Tests

Figure 5.9 Checking for the Tower Crane Capacity – Scenario 3, Crane Capacity Tests

Figure 5.10 Checking for the Tower Crane Capacity – Scenario 4, Crane Capacity Tests

Figure 5.11 No Solution Available – Scenarios 5, Crane Capacity Tests

Figure 5.12 GA Performance in 5 Independent Runs of each Scenario from 1 to 4 - Crane Capacity Test Series

Figure 5.13 The Tower Crane Layout – Symmetric Layout Tests

Figure 5.14 Results of the Optimized Tower Crane Layout – Scenario 1, Symmetric Test Series

Figure 5.15 Results of the Optimized Tower Crane Layout – Scenario 2, Symmetric Test Series

Figure 5.16 Results of the Optimized Tower Crane Layout – Scenario 3, Symmetric Test Series

Figure 5.17 Results of the Optimized Tower Crane Layout – Scenario 4, Symmetric Test Series

Figure 5.18 GA Performance of Independent Runs in Each Scenario from 1 to 4 – Symmetric Test Series

Figure 5.19 Tower Crane Layout – the Number-of-Crane Tests

Figure 5.20 Total PUNGGOL Site Layout – Poh Lian Project

Figure 5.21 Tower Crane LC-2074

Figure 5.22 Key Plans of Two Groups of Blocks 635A-635B-635C and 636A-636B in PUNNGOL Site

Figure 5.23 Site Layout of Block 636A & 636B – PUNGGOL Site

Figure 5.24 Layout of Vertical Members (Precast Columns, Walls, Chutes and Core Lifts) of Block 636A & 636B – PUNGGOL Site

Figure 5.25 Layout of Horizontal Members (Precast Beams) of Block 636A & 636B – PUNGGOL Site

Figure 5.26 Layout of Horizontal Members (Precast Flanks) of Block 636A & 636B – PUNGGOL Site

Figure 5.27 Site Layout of Block 635A, 635B & 635C – PUNGGOL Site

Figure 5.28 Layout of Vertical Members (Precast Columns, Walls, Chutes and Core Lifts) of Block 635A , 635B & 635C – PUNGGOL Site

Figure 5.29 Layout of Horizontal Members (Precast Beams) of Block 635A, 635B & 635C – PUNGGOL Site

Figure 5.30 Layout of Horizontal Members (Precast Flanks) of Block 635A , 635B & 635C – PUNGGOL Site

Figure 5.31 GA Performances of 4 Independent Runs in Scenario 1 – The First Typical Cycle of Installation (2^{nd} and 3^{rd} Floors) - Block 636A & 636B – PUNGGOL Site

Figure 5.32 GA Performances of 4 Independent Runs in Scenario 2 – The Last Typical Cycle of Installation (13^{th} and 14^{th} Floors) - Block 636A & 636B – PUNGGOL Site

Figure 5.33 Optimised Tower Crane Layout of PUNGGOL Site

Figure 5.34 Actual Tower Crane Layout of PUNGGOL Site

Figure 5.35 GA Performance of 2 Independent Runs For the Installation of Structural Precast Components in the 2^{nd} Floors - Block 635A&B&C - PUNGGOL Site (the Optimised Solution vs. the Actual Solution Chosen on Site)

Figure B.1 Total Site Layout – Poh Lian Project

NOTATIONS

C_{total}	The total rental cost of all cranes used
H	The maximum standing height requirement of the tower mast
h_{bd}	The height of the building
h_{ge}^{i}	The total height of the lifted gear for module i
h_{in}^{i}	The installation height of the module i
h_{md}^{i}	The maximum height of module i that needs to be installed
h_p	The vertical distance from the hook to the boom of the crane
h_{sf}^{i}	The safety height of the module i
J_k^i	The number of tasks assigned to crane i in batch k.
L	Possible location of tower crane
L_{binary}	The total length of the CLP chromosome with binary bit encoding
$L_{integer}$	The total length of the CLP chromosome with integer encoding
l_j	The horizontal distance between demand point and supply point
NC_{ik}	The conflict index between crane i and k
$N_{available}$	Number of cranes available in the database
N_{crane}	Number of cranes used in the project
$N_{location}$	Number of possible crane locations
N_{module}	Number of lifted modules
N_{supply}	Number of supply points
N_{small_group}	Number of small groups
N_{pop}	The number of chromosomes in the population
$N_{generations}^{best}$	The number of generations without improvement of the best solution
$N_{generations}^{total}$	The total number of generations
$n_{ij,kl}$	The number of intersections of two triangles, of which apexes represent the crane location, the supply point, and the demand point of the two tasks
Q	The maximum load
$[Q]$	The ultimate weight capacity of the cranes at the relative radius

Q_{ij}	The number of lifts of j^{th} task groups which is handled by crane i
q_{md}	The weight of the module which needs to be installed
$\sum q_t$	The total weight of the hook, and all the hangers
P_{mut}	Permutation Rate
$P_{replace}$	Replacement Rate (Percentage of the population will be replaced during each generation.
P_x	Crossover Rate
$T(D_{j-1},S_j)$	The hook traveling time from the last demand point (D_{j-1}) to the supply point (S_j) of lifted assignment j (without load)
$T(S_j,D_j)$	The hoisting time for lifted assignment j from the supply point S_j to the demand point D_j (with load)
T_a	Time for trolley tangent movement
T_h	And the hook vertical travel time
$T_L(S_j)$	The delay time for loading at S_j
$T_U(D_j)$	The delay time for unloading at D_j
T_v	The hook horizontal travel time
T_w	Time for trolley radial movement
T_{total}	The total hoisting time of all cranes used
T_m^{delay}	The delay time of crane m
T_k^i	The hoisting time of crane i in batch k
T_{Hook}^n	The hook travel time for the n^{th} request
$T_{hoisting}^i$	The total hoisting time for crane i, counted from the beginning of the overall installation to the time finishing the last lifted module.
t_k^e	The finish (end) time of the k^{th} batch
t_k^s	The start time of the k^{th} batch
t_{ij}^e	The finish (end) time of task i-j
t_{ij}^s	The start time of task i-j
t_{i-j}^k	The hoisting time of crane i to lift task j in batch k.
V_a	The radial velocity of trolley (m/min)

V_h	The hoist velocity of hook (m/min)
V_w	The slewing velocity of jib (rpm)
α	Parameter represents degree of coordination of hook movement in radial and tangential directions in the horizontal plane
β	Parameter represents degree of coordination of hook movement in the vertical and horizontal planes
Δt	The overlap time period
$\rho(D_j)$	The distance between crane location and demand point of task j
$\rho(S_j)$	The distance between crane location and supply point of task j

ABBREVIATIONS

ANN	Artificial Neural Networks
BSI	British Standards Institution
CAG	Crane Assignment Genes
CD	Crane Database
CDG	Crane Database Genes
CEI	Choice Efficiency Index
CLG	Crane Location Genes
CLP	Crane Location Problem
CX	Cycle Crossover
FLP	Facilities Layout Problem
GA	Genetic algorithm
NC	Conflict Index
NP-hard	A complexity class of decision problems
OM	Optimization Module
OPMX	Open Partial-Mapped Crossover
PD	Project Database
PMX	Partial-Mapped Crossover
PPAM	Pre-Process Algorithms Module
SPG	Supply Point Genes
TSP	Traveling Salesman Problem

CHAPTER I: INTRODUCTION

1.1 Background Information

The appropriate definition of crane may be that of Shapiro (1999): "A crane is a self contained piece of equipment, which lift and lower loads by means of ropes and pulleys and move the loads horizontally". This section introduces the general usage of cranes as hoisting machines in the construction industry. Research efforts to optimize crane usage are presented.

1.1.1 The Usage of Cranes in the Construction Industry

It is estimated that 35-45% of the cost of building work is spent on materials, and in civil engineering, the corresponding value sometimes approaches 35% (Harris, 1989). According to the study by Proverbs and Holt (1999), costs of materials handling range from 30 to 80 per cent of total construction cost (i.e. building cost). Material transportation is therefore one of the most important activities on the construction site. Building materials like steel frames, temporary formwork, concrete, precast components and other objects such as building equipment need to be lifted and moved horizontally to the installation positions or work platforms. This lifted work relies heavily on the crane – the key piece of equipment on site. Gray (1983) in the research into the consequential cost implications of design decisions highlighted the central role that the primary lifting devices (predominantly cranes) have on the control and pace of construction operations. There are two broad categories of cranes, namely tower cranes and mobile cranes. In each category, due to the differences of types of mounting base, types of boom and other components, each crane has its own special and distinguishing hoisting mechanisms and characteristics that may best serve a certain lifted work in the construction project. Thus, the type of lifted work has a profound effect upon the choice of crane to perform the task, and the speed of work has a similar effect on the construction operations (Gray and Little, 1985). A wrong choice of crane is likely to have serious consequences, such as violating safety principles when operating an under-capacity crane, or requiring a change of the crane halfway through the project which usually results in uneconomical construction and/or longer construction duration. On the other hand, the choice of a suitable crane for a particular project in the design stage will result in lower construction cost and the lifting work will be done more effectively with reduction in construction duration. The lifting task is a complex matter that is closely related to the tasks to be performed since there are many types of lifting in terms of the nature and the scope of work in construction projects. For high-rise construction where the vertical transportation of materials is crucial and critical, the tower crane, which has the advantage of high and extensible tower mast, is becoming dominant among other types of cranes. It is not an exaggeration to say that 'hoisting' (vertical movement of materials) is the most important single factor in the success or otherwise of the building of a high rise project (Herbert, 1974). If the hoisting plan is good, success is likely to follow. Hence, the proper planning and usage of tower cranes is of paramount importance in this type of building construction and this is the focus of the present study.

1.1.2 Optimisation of the Usage of Cranes

Since cranes take an important role as discussed above, the planners should start planning for crane usage during the pre-construction planning stage or even in the tendering stage. The aim is to optimize crane usage by selecting the right type of crane and positioning the tower crane at the optimum location. Once the crane is chosen, practitioners attempt to maximize the utilization of the machine on the site (Gray and Little, 1985). In practice, the planners try to ensure that the crane is not left idle because of waiting for loading request. Specifically, during the construction stage, the planners would prepare a daily hoisting schedule to ensure that the tower crane is able to serve the crane related activities continuously. Another method of ensuring that the crane is not under-utilized is by using the staggered construction method. In this construction method, the building is divided into equivalent sections with a repetitive procedure of building task. Hence, the crane and other resources are utilized consistently during the construction period. These practices are fundamental approaches to optimise the crane usage. Other developed approach links to the facilities layout problem (FLP), in which the crane location(s) and its supply points are arranged on site to enhance the lifting work. However, this approach may encounter difficulties due to the vast number of trades involved and the interdependent planning constraints (Tam et al., 2001). The optimization of tower crane usage is still based on human judgment of experienced project managers.

1.2 Objective and Rationale of the Study

The objective of this study is to build a computer model to optimize the tower crane usage in high-rise precast concrete buildings. The tower crane usage includes the selection of suitable tower models among the available cranes in the market for a particular project, the selection of the tower crane operating locations, the arrangement of the supply point locations to support the crane activities and the distribution of the lifted jobs among the multiple cranes used. The model attempts to minimise the total hoisting time of cranes and other related factors such as the tower crane rental, the collision possibility and propose an order of safe installation. The study also aims to understand safety of hoisting activities on site.

This study is important for a number of reasons. Firstly, although precast concrete construction often requires significant crane work during installations, there has not been any model to optimize the usage of the tower crane in this type of construction. Thus, their usage is determined through trial and error, mostly based on the experience of practitioners with little quantitative reference (Zhang et al., 1999). Lastly, there are still cases of improper usage of cranes that result in serious crane accidents. The consequences might be either uneconomical construction, or delay in construction progress.

1.3 Methodology of the Study

The usage of tower cranes is empirical. It is helpful to be familiar with the cranes, their special design and configurations as well as their typical applications. A computer model for crane usage needs to be built on real site practice to avoid over-simplifications and to ensure an adequate reflection of reality. It is also essential to note that successful engineering practice of crane usage requires more than analytical tools and rules of thumb (Shapiro, 1999). Bearing in mind these issues, particular attention and efforts are made to:

(1) Review the literature regarding the usage of cranes on site, and the current methods employed to maximize its usage.

(2) Conduct site observations, interview practitioners to learn more about practical experiences on the use of tower cranes.

(3) Develop computer program to optimise the tower crane usage. The model is then tested through a series of simulated scenarios, and practical case studies.

1.4 Scope and Limitation of the Present Study

The scope of the present study is on the use of tower crane in the installations of structural precast components in high-rise construction projects. The main interests are to enhance safety and productivity of the lifting work in this type of construction.

Concerning safety, the model implements a safe construction sequence and eliminate crane accidence by specifying each crane a safe working zone (usually a different building block). In the case that multiple cranes work in the same building block, one source of crane accidents may be the collision between cranes, particularly during their operations. A model to control collisions between two saddle-boom tower cranes is proposed in section 3.1.5. Particular constraints and assumptions of the model are discussed further in the following chapters.

1.5 Organisation of the Thesis

The dissertation is organised into **six** chapters and a brief outline of these chapters is highlighted below:

- **Chapter 1** introduces the usage of cranes as lifting machines as well as traditional approaches to optimize this kind of machines in the construction industry. Chapter 1 also highlights the objective, rationale, scope, and limitation of this study.
- **Chapter 2** provides literature review of previous research related to crane usage optimization. The author will present critical evaluations and discussions about the previous approaches.
- **Chapter 3** addresses a number of issues related to the crane location problem (CLP), with definition of the problem and its expected solutions.

- **Chapter 4** presents the detailed implementation of CLP using Genetic Algorithms (GA) including the problem formulation as well as the customized GA operators. Selected tests to optimize GA parameters are also provided in this chapter.
- **Chapter 5** discusses the possible applications of the GA model for CLP in the construction planning stages. Selected small examples and case studies are also included.
- **Chapter 6** summarises the main findings of the study and the future development of the model.
- **Appendix A** contains the pseudo-code of the program for the customised GA operators.
- **Appendix B** includes the data of a large-scale precast project at Punggol site which has been investigated in detail in this study.

CHAPTER II: LITERATURE REVIEW

2.1 Approaches for Optimising Crane Usage in Construction Industry

Effective planning demands competent and experienced personnel whose primary responsibility is to determine material and equipment handling methods for the proposed construction work (Proverbs and Holt, 1999). The equipment handling method was identified as an essential part of construction planning (Masterton and Wilson, 1995). Warszawski (1973) first defined the analysis of material handling methods. In this paper, he pointed out that one of the important problems in construction planning was quantitative evaluation of the transportation methods on the building site. He classified the equipments for material handling into three groups, namely (1) linear lifting system such as dumper, wheel barrows, handcarts, trucks etc.; (2) tower cranes; and (3) mobile cranes.

The most common and effective hoisting equipments are mobile cranes and tower cranes. Tower cranes are suitable for handling of relatively light loads to extremes of height and reach, particularly where the space for crane standing is confined (BSI, 1972). On the other hand, mobile cranes are used where onsite or between site mobility is a primary requirement or where the job duration is short. They are usually adaptable to a wide variety of job applications and environmental conditions. There is a large number of crane manufacturers, including Liebherr, Comansa, Potain, Carlo Raimondi, Terex Towers, MAN-Wolffkran, Condecta, IHI, Jaso, JCB, Tornborgs, and Kitagawa (IC report 1999), that produce a wide variety of crane models for each type of cranes. Thus, the crane market is huge and accompanied with plenty of different procurement alternatives.

There are two main approaches to optimize the crane usage. They are (1) selection of suitable type of crane for a particular project and (2) designing the site facilities layout for the best tower crane operations. Since the crane locations and its supply points are the centre of the site facility layout in the construction project, the latter approach is called the crane location problem (CLP). The CLP is the focus of this study and is discussed in more detailed in the subsequent sections.

2.2 Crane Location Problem

In high-rise construction, a typical floor is completed within 5 to 10 days. Such high rates of production result in considerable flow of materials from ground level, material ports etc. to working area in both vertical and horizontal directions, and thus requiring an efficient transport system. In this aspect, a crane is the pivot or even 'bottleneck' between material flow and can set the pace of work (Zhang et al., 1996). It can be seen that determining an optimum position for tower crane is critical in a construction project since it will enable the planners to make full use of the tower crane for transportation of materials horizontally as well as vertically. The crane location problem should cover the planning of site layout facilities including supply centres and equipments because the positions of those facilities directly affect the transportation of materials on a building site. An analytical evaluation of transportation time is obviously helpful and often essential in the planning of various construction activities on a building site (Warszawski, 1973). Research has been carried out to build a quantitative evaluation of transportation when determining the location of tower crane(s) on a construction site and the crane location models have evolved over the past 30 years. The optimum crane location should not only satisfy all site constraints and operating constraints but also create the best conditions for the lifting operations in the construction process. Previous research works have tried to address those issues, overall or in part, using different methods such as exact methods and heuristic methods in the form of simple algorithms, rule-based systems, decision support expert systems, and artificial intelligence. The same characteristic of these studies is the use of computer as a tool to aid the planning process, but in different levels that are referred as “ad-hoc”, “little”, “average” and “extensive”.

The first approach with “little” use of computer consists of simple algorithms, decision flow charts, aiming graphical interface and expert systems. Warszawski (1973) first established a time-distance formula by which quantitative evaluation of location was possible. He argued that the optimal location might be obtained by minimization of transportation distances and thereby the costs of labour and equipment involved with, or dependent upon the transportation. Rodriguez and Francis (1983) proposed a model in locating the parking position of the crane hook between movements. They tried to find the optimum position of the crane hook to minimize the total transportation cost between a number of supportive facilities in the construction site. The model works with the assumption that the (single) crane location, and its supportive facilities as well as the transportation cost weight factor for each facility are pre-determined. Farrell and Hover (1989) developed a database with a graphical interface to assist in crane selection and location. Most of these research works singled out the tower crane, the most critical facility in high-rise building construction, as the target of optimization. Their goal is to prevent crane accidents due to improper planning and crane selection. They argued that, in their respective concern, crane safety could be obtained by ensuring adequate crane capacity, and placement of crane with due considerations of overhead power line and other hazardous area such as steep inclines, soft soil, rights of way, and office trailers (Farrell & Hover, 1989). With the aids of computer graphics, multiple cranes might be chosen and positioned on site on a trial-and-error basis. Efficiency and safety might be obtained but with no quantitative appraisal in terms of productivity enhancement in this work.

Apart from the algorithmic approaches, rule-based systems have also evolved to assist decisions on crane numbers and types as well as their site layout. Furusaka and Gray (1984) presented a dynamic programming model for regular shape buildings with the objective function being cranage cost (including the cost of hire, assembly and dismantling), but neglecting the effect of crane capacity to the working duration. The location of crane was defined by simple grid line of span dimension (at the centre of each square) and its coordinates were taken into account for the reach requirement only. Gray & Little (1985) first tried to position tower crane in irregular-shaped buildings using rule-based system. They developed a computer program that first used graphics to help user to consider the implications of building's shape, load distribution and possible crane location, then asked user to provide information to guide them through decision flowcharts. Later, Gray (1987) summarized the work above and called their computer program CRANES, which is considered as an expert system in which the user can examine the output and locate a suitable location for the crane to minimize the size of the crane with due considerations for access and dismantling. The author also tried to assess the impact of crane usage on the progress of the work, and thus the project schedule. Chalabi and Yandow (1989) developed another rule base program called CRANE. CRANE contains more than 100 rules about tower cranes, and is able to perform geometric calculation associated with the selection process as well as providing graphical output. Warszawski and Peled (1987) claimed to build an expert system for crane selection and location that was able to handle non-quantitative factors in the construction planning tasks. The program called LOCRANE was to present the user with the feasible alternative solutions and guided him to select the optimal one. Subsequently, Warszawski (1990) compared the two systems, rule-based system CRANES and expert system LOCRANE, and indicated the advantages of expert system in its ability to handle non-structured and uncertain information. He also pointed out the main limitation of the two systems as over simplification of real life situations (Warszawski, 1990). Using the above systems, the users are required to provide information by answering numerous questions during the selection process. These programs usually provide recommendations for a particular set of input. However, the user should have basic knowledge of the construction process and tower cranes to be able to reason the provided solutions from the program. There is also no quantitative reference in terms of productivity enhancement obtained by those models. One of the remarkable attempts to solve the crane location problem is the study of Choi and Harris (1991). In their article named "A model for determining optimum crane position", Choi and Harris presented a general method to solve the single stationary-crane location problem for cast-in-situ construction project. They developed a mathematical and normative model to determine the optimum location of a crane in a construction site with its supportive facilities such as supply points and storage areas. The objective function of the model is minimization of the total crane transportation cost between crane and the construction supportive facilities that are serviced by the crane. Thus, the optimum crane position is determined by obtaining the least total transportation cost. The data requirements of the model include the positions of the facilities and the proposed crane location in terms of coordinates, the weight of economic lift of each type of load, the inter-facilities relationship in term of percentage weighting, the average angular and radial movement speed of the proposed crane. The average load was calculated as the portion of the total load to be lifted from one facility to another facility and the average economic lifts of each type of lifting elements involved. They also recommended the average economic lifts of different type of elements such as 1.25 ton for concrete (including skip); 2.20 ton for steel reinforcement; 1.0 ton for formwork; and 1.0 ton for sundry items. The Choi and Harris's model first formulated the components of hoisting time operations, although simplified, and it broke new ground for the development of computer model concerning the crane hoisting time. Subsequently, Emsley (1992) proposed several improvements to the Choi and Harris model such as the implementation of physical constraints in terms of minimum and maximum radii and lifting capacity of the crane, the transportation in the vertical plane, the parameter to control the movements within horizontal plane and between planes, and the presence of additional balancing movement. These proposed improvements have been solved successfully by Zhang et al., (1995, 1999), and will be reviewed in the later section.

The second approach with the "average" use of computer refers to more advanced computer techniques that take into account the lifting operations (i.e. formulating the hoisting time model for the lifting job and considering other related constraints). For instance, Wijesundera and Harris (1986, 1989, and 1991) designed a "dynamic" simulation model to reconstruct operation times and equipment cycles when handling concrete in cast-in-situ construction project. However, due to the nature of pouring concrete operations on site, no consideration was provided to service sequence in this study. Zhang et al., (1995, 1996) built a stochastic simulation model to reconstruct the process of lifting operations of crane from supply point to demand point. The model took into account the balance of hook movement - the return movement from the previous demand point to the new supply point of the next lifting job in unloading state. The model was presented to optimise a single crane location. The authors claimed that the model could help to save approximately 20-40% of crane travelling time in horizontal plane. The model requires that the number of lifts between a pair of supply point and demand point (S-D pair) is large enough, thus it is suitable for cast-in-situ concrete project where the material transportation is in batch manner between an S-D pair (unloading point). Subsequently, Zhang et al., (2001) developed their model for multiple cranes. The upgraded model, with a task grouping sub-model using Monte Carlo simulation (to assign groups of task to different cranes), is aimed to enhance the utilizations of all the cranes involved by balancing the workload and minimizing the likelihood of conflicts between them. Although their form of crane conflict control is simplified, it is probably the first attempt to tackle the multiple cranes collision problem quantitatively. The work of Zhang et al., (1995, 1996 and 1999) in the form of a methodology in task grouping and a few parameters to measure the efficiency of each task grouping like conflict index NC, and workload standard deviation σ, provides a good computer tool to solve the crane location problem and indeed raises a number of important issues for CLP. However, these models are only suitable for cast-in-situ construction project. For precast construction projects where the continuous number of lifts between an S-D pair is usually as small as one or a few only, their simulation model might not behave well. It is because in the former type of construction, the lifting sequence is not so important while in the latter type of construction, the installation of precast element has big impact by their sequence.

The last approach with the "extensive" use of computer refers to the work in which researchers adopt artificial intelligence approach to solve the CLP. Perhaps the most popular artificial intelligence techniques to mention are the genetic algorithm (GA) and the artificial neural network (ANN). Genetic Algorithms has been proved to be a potential tool for solving large-scale combinatorial optimization problems (Jaramillo et al., 2002). While this class of problems is known to be very difficult to solve, it has many engineering applications. Since the 1980s, GA has been applied to solve many real world problems. Jenkins (1997) tried to find the optimum combination of design variables for structural design optimization by GA. Chan et al., (1996) used GA to solve the construction resource scheduling problems, where GA acts as a scheduler and is found to compare well against other heuristic methods. Lam and Yin (2001) presented various applications of GA to transportation optimization problems while Jaramillo et al., (2002) tried to evaluate the performance of GA as an alternative approach to solve general location problems. GA is also employed to solve site facility layout problems, such as in the work of Li and Love (1988) and Philip et al., (1997). They tried to use GA to optimize a set of pre-determined facilities. Yet, their model was simplified, with the shapes of facilities considered rectangular, and not much consideration has been made to assess the capacity constraints and the inter-relation between these facilities. Tam et al., (2001) tried to employ a GA technique to optimize the location of a single tower crane and its supply points for the conventional cast-in-situ concrete construction project. Consequently, they introduced a new part to their GA model, using ANN to predict the hoisting time of a tower crane (Tam et al., 2003). However, their GA model is so simple that it works for a single crane only. In addition, the authors used average configurations of hoisting velocity, trolley movement velocity and slewing velocity of boom in their hoisting time model to focus on the effects of crane locations and supply point to the total transportation time. However, they were unable to compare the effectiveness of different crane configurations (of different crane models) to the total hoisting time.

In summary, all the previous models/programs for the crane location problem (CLP) are either too simple to emulate the real life practice (due to over-simplification of practical constraints) or not relevant to the scope of this study (i.e. the installation of precast structures). In fact, most of the previous models are used for tower crane work in the conventional cast in-situ concrete projects where the lifting sequence are not so important due to a large number of lifts between a pair of supply point and demand point (a S-D pair). In contrast, the lifting sequence is important in precast construction projects since the number of lift between a S-D pair is very small, usually 1 or 2 only.

In this situation, the lifting sequence may result in significantly different hoisting time due to the balance movements. Thus, the existing models may not work well in this type of construction and there is currently no available program to optimize the crane work in precast construction projects.

2.3 Summary of Literature Review

Facilities layout is a science that considers the existence, positioning, volume and timing of the temporary facilities used to carry out a construction project (Michael et al., 2002). Since the layout of the facilities can affect directly the productivity of the construction work, a suitable management strategy can be the key factor to successful completion of a project within the targeted period. However, the management of facilities layout is a very difficult task, which usually subjects to a number of trades and related planning constraints. The task is even more complicated in high-rise building projects, where the allocation of temporary facilities keeps changing and is continually adjusted with the progress of the construction work (Tam et al., 2001).

In high-rise construction, whether using cast-in-situ or precast concrete, the vertical material transportation is of paramount importance and most of the work is handled using tower crane(s). Therefore, the tower crane and its supply point locations become the key factors of the temporary site facilities layout for high-rise construction projects. Optimisation of the tower crane(s) locations and its supply point(s) then is the most important part of facilities layout planning. In practice, tower crane position(s) are usually determined through trial and error method, considering site topological layout and overall coverage of tasks as well as the surrounding environment (Zhang et al., 1999). These factors vary from one project to another, thus resulting in different site layout strategies and approaches. This fact makes the CLP, which is recognized as nonlinear and discrete optimisation problem, difficult to solve by scientific approach.

The solution for this problem still relies on experienced judgment of designers and thus there exists multiple solutions with little quantitative reference.

Research into the development of various crane location models has been on-going over the past 30 years. Lessons can be learned from previous research. However, most of the work has limitations in either over-simplification or lack of consideration of the site conditions (Zhang et al., 1999), or to be more specific, neglecting the inter-related effect between locations of the tower crane and supply points (Tam et al., 2001). Another limitation is that most of the models involve single tower crane only, and little work has been done to model the optimum location for a group of tower cranes. All the above-mentioned limitations, acting as single shortcoming or in group, have constrained these models from being used regularly by practitioners. Hence, there is necessity to build a "more realistic" model, which considers as much as possible the related factors to overcome the shortcomings of previous models to make it applicable in real life practices.

CHAPTER III: CRANE LOCATION PROBLEM (CLP)

3.1 Discussion about CLP

This section aims to give a detailed discussion on how to evaluate a solution for CLP. The key factor is to have an in-depth study of the problem, since good understanding of the problem facilitates reasoning of the "best solution" given by a computer model.

3.1.1 Possible Locations of Tower Cranes

Locating the crane positions at the centre of the site facility layout works for high-rise construction project (as discussed in section 2.3). Many factors need to be taken into account when determining the tower crane locations, such as the site area and its constraints, the building and its components, the cranes themselves and their operational characters, and the statutory regulations relating the usage of tower crane. Some of these factors will be discussed in detail in sections 3.1.1.1 to 3.1.1.6.

3.1.1.1 Site Area and Its Constraints

Site area and its constraints refer to the environment in which the crane performs its job. This group of factors has a great effect to the choice of the tower crane's location. The ideal location for a tower crane should be outside the building footprint to which there is vehicular access to within at least 10 meters since this creates favourable conditions for the erection and dismantling operations for the tower crane. However, this ideal location may not be possible to obtain in some cases due to the restriction of the site area or other site constraints such as the existence of surrounding buildings and underground structures. For example, the crane should not be sited where there is a danger to its foundations or supporting structure from cellars, temporary shorings, excavations, embankments, and buried pipes, etc. (BSI, 1972) or the crane foundation must be cleared of underground obstructions such as septic tanks, underground power and gas lines (Dieleman, 2002). In addition, considerations must be made to ensure the safe operations of the tower cranes to prevent the conflict between the boom of the crane and any part of the existing structures, or to provide a firm, stable and adequate bearing capacity foundation for the crane regardless of the seasonal soil conditions of the ground. The crane should be supported on a good foundation, and tied to a permanent or temporary structure that is sufficiently strong to carry the maximum loads that the crane may exert upon, both in service and out-of-service. If the site has access problem, which is very common for congested urban high-rise project, loading and unloading of materials need to be carried out by tower crane from the road-side to storage yard or working area. In this case, the location of tower crane is selected such that it can also better serve that activity.

3.1.1.2 Coverage Requirement

Another critical factor in determining the position of tower cranes is the coverage requirement. The primary consideration for the tower crane is to ensure that it can cover the whole plan area, plus the material storage areas and loading points. The tower cranes must be located at such a place where it is possible to provide 100% or almost lifting coverage over the plan area of the building. It may be advisable to locate the tower crane as near the perimeter of the building as possible since the crane can cover the building effectively with a much shorter jib. Shorter jib obviously results in smaller induced bending moment in the mast, but also a lighter and cheaper crane structure. In large sites, where the lifting jobs are scattered in a broad area and one crane cannot provide 100% coverage, multiple cranes might have to be used to provide sufficient coverage, and it may be economical to place the tower crane close to the location with high frequency of lifting jobs.

3.1.1.3 The Building and Its Components

This group of factors refers to the characteristics of the building and its components that may affect the selection of the crane location. Two of the most influential factors in this group are the building height and the weight of the heaviest components to be lifted. In the evaluation of crane capacity, the additional weight of slings, spreader beams or other lifting gear necessary for the safe handling of any particular unit must be taken into account (Illingworth, 2000). The required capacity is also related to the location of tower crane in terms of the concentration area for the modules and their weights. It is advisable that the tower crane should stand near the concentration area of the lifting jobs as well as the positions of heavier loads since this can help utilize the crane the most. With regards to building height, if the building is higher than the maximum freestanding height of the tower crane, the location of the crane should be near the building such that its mast can be tied to for lateral supports. Practical distance between the mast and the nearest reliant structures should be in the range 2-5 meters. Shorter distance may pose possible conflict between the foundation of the crane and the foundation of the structures while longer distance may lead to difficulties in attaching the ties. If the crane foundation is placed on or be part of the structure, further considerations relating to the structural capacity of the structures subject to maximum imposed load from the tower crane must be investigated.

3.1.1.4 The Cranes and Their Operational Factors

The location of a tower crane also depends on its type and its configurations. For example, the boom of a crane relates closely to its coverage capacity. Generally, a luffing-jib crane requires less tower but hammerhead cranes have greater freestanding height and greater distances between jumps (Dieleman, 2002). The crane should be located where it can reach the farthest pick. It should also be noted that the boom or the tail swing of the crane can collide to existing obstruction on or near the jobsite such as high power lines, buildings, bridges or future obstructions such as cranes or other equipment to be used or erected on the project. Therefore, the type of boom/jib or the height of tower mast should be selected to prevent possible collision in such situations. Another aspect to consider is selecting the crane location with regards to its assembling and dismantling procedure. Since most of static base tower cranes are transported in parts to site and assembled on site, it is necessary to check if the proposed crane location has enough space for that procedure. Precautions also have to be made to consider the dismantling procedure of the tower crane when it finishes all the jobs. At this stage, the tower crane can use its own mechanism to lower its boom and another small mobile crane to help to dismantle it. If the tower crane cannot lower its booms (e.g. due to restraints with the building); it may require a big mobile crane from the ground to dismantle the tower crane. In such case, the crane location chosen should satisfy the space requirements for these procedures.

3.1.1.5 Statutory Regulations

There are a number of applicable standards that stipulate the safe use of tower crane, including OSHA, ANSI and DIN, etc. Most of them require an erection/dismantling and operation plan with strict safety certifications. For example, the use of tower crane in the construction site near Mass Rapid Transport (MRT) is not permitted in Singapore as a collapse may collide into MRT structure or MRT train. In special cases, permission and clearance must be obtained, and limit switches need to be installed to ensure safety.

3.1.1.6 Locations for a Group of Tower Cranes

For a construction site that employs multiple cranes, the considerations to locate a group of tower cranes are more complicated. In this case, the building should be sectionalized according to the physical characteristics of the project to establish the locations of multiple tower cranes. A potential problem, which must be checked especially for saddle jib tower cranes, is the location of cranes where the horizontal boom intersects the mast of another tower crane, or the jibs clash (Gray and Little, 1985). The solution may require the jibs to be located at different heights, or alternatively, to install limit switches to prevent booms from colliding into each other. In the interests of safety and efficient operations, cranes should be located as far apart as possible to avoid interference and collisions, on the condition that all planned tasks can be performed (Zhang et al., 1999). However, this ideal situation is often difficult to achieve in practice; constrained work-space and limitations of crane capacity make it inevitable that crane areas overlap. Hence, precautions have to be made to prevent multiple crane collisions. Further discussion about this matter is given in section 3.1.5.

3.1.1.7 Summary about Tower Crane Locations

In summary, the crane should be located at the position in the feasible region that satisfies all the constraints mentioned above. However, practitioners find it difficult to obtain a near optimal solution without consideration and reasoning on the complex interacting factors. Evaluations can be made by using a multiple-objective model that calculates the trade-off among the criteria to generate a satisfactory solution. However, the relations between those criteria are very difficult to establish because their weight of importance differs from project to project. A systematic approach is proposed to find the feasible regions for tower crane location (See section 3.2.1.1).

Generally, there are usually many of separated regions where the tower cranes can be located. The decision on tower crane layout with due consideration for these possible alternatives is not an easy task and practitioners decide intuitively rather than through a scientific approach together with quantitative reference. They need to optimise the selection of possible crane location(s), with consideration of all site and project constraints. The objective of this optimisation is to choose the best location among the possible ones.

There are two aspects for the decision of crane locations, finding the feasible solutions and choosing the best one(s) from them.

3.1.2 Supply Point Locations of Tower Crane

Crane supply point locations are those places that store and directly deliver pre-cast elements to the tower crane. The location(s) of tower crane(s), the space requirement to store lifting elements, the truck access to that location for handing over the lifting elements need to be considered to determine supply point locations [*3.1*]. The supply point should not obstruct the internal transportation paths on site. If the site is too congested, it might be impossible to arrange any supply point. In this case, the just-in-time supply policy, i.e. the resources to be delivered directly from trucks, might be considered. In short, the supply point(s) should be located at the positions to support the crane activities. It must be accessible for the handling over resources from external contractors (e.g. pre-casters) and convenient for other internal transportation functions. The supply point should also have enough space to store the estimated resources within a time-period so as to ensure the continuous operations of the tower crane.

The selection criterion to choose supply points should be based upon the productivity of the lifting work.

[*3.1*] The capacity of supply points may also affect the supply plan of providers and may cause double handling due to the lack of space. In this case, the resources have to be stored temporarily somewhere else on site or off site and later transported to the supply points when needed. Those procedures require additional crane work to transport the resources from truck to the temporary storage and from that temporary storage back to supply point (that originates the name double handling). Double handling makes the crane work inefficient, may result in delay of work and thus it should be prevented.

3.1.3 Lifting Assignment Policies

Lifting assignment policies refer to the selection of supply points to store the lifted elements or modules and the selection of the tower crane that performs each lifting task. The interdependency between crane location and crane supply points, as mentioned in Tam et al. (2001), with different tower crane locations may require one or more different supply point locations for the most efficient lifting work, and vice versa. This mutual relationship between tower crane location and its supply point location is demonstrated in section 5.1.3. Besides, the task assignment policies should also take into account the capacity of the supply point as well as the appropriate distribution of the lifting work among a group of cranes. After all, the task assignment policies are to acquire high work efficiency of the crane. Thus, the lifting assignment policies should be chosen to obtain the shortest installation time and the best lifting schedule.

On the other hand, concerning with the scaling problem of CLP mentioned in section 3.4.1, it is necessary to group single lifting tasks into small groups with an assumption that they are all performed by a single tower crane and stored at the same supply point. This technique is called task grouping, which helps to save computational effort. The task grouping follows the condition that the new group formed by individual lifting tasks should not require a bigger capacity crane. A crane, assigned to a group of lifting tasks, should have sufficient capacity to perform any single task in the group. Therefore, only the lifting tasks with similar characters such as the same type of elements (the same weight), in a small region of installation locations (referring to the reach requirement) might be grouped. Additionally, lifting tasks belonging to the same space of construction should be grouped.

3.1.4 Lifting Sequence – Installation Order

It is advisable that the planning process should be planned prior to the actual implementation of the project. The schedule of components and their sequence of erection should be established at the earliest possible moment – if possible at the tender stage as suggested by Illingworth (2000). Traditional heuristic methods typically follow three steps: planning, sequencing then scheduling. The sequence of erection can be examined after the supplier's schedule of precast units has been completed. It is widely accepted that there will not be a standard erection sequence. It depends on the structural system used as well as the type of precast elements and type of joints used. It is also contingent on the size of the project as well as the mechanical and electrical (M&E) services involved. Technically, the sequence of erection of precast components is defined by the considerations of precedence and resource constraints. The precedence of each lifting task is identified by the structural considerations as well as the construction methods.

3.1.4.1 Installation according to Batches

In general, in the conventional construction method where the building is built from the foundation up, the construction sequence of main structures follows the vertical direction. That is, the installation of the beam should be postponed until the two columns below it are installed and gain enough strength to resist the load from the beam. For a precast building with basic fabricated components such as columns, beams, façade walls and floor slabs, the order of construction in a typical construction sequence might be:

1. Installation of the columns (that may be of one or few story height)
2. Installation of the façade walls
3. Installation of the beams

4. Installation of the floor slabs

Then steps 2, 3, and 4 may be repeated until a new batch of columns needs to be installed. It is reasonable to assume that all the precast components of the same type on the same floor are installed in a continuous period. These components are called a batch. The components of the next batch must wait until all the components of the present batch are installed. Different types of components (such as columns and precast wall) can be installed in the same batch if their erection order does not violate the installation process as well as satisfies other construction constraints. The erection sequence for the main types of precast components seems to follow the vertical direction of the building, and thus they can be classified into different batches according to the height of their installation position.

3.1.4.2 Installations of Small Groups in the Same Batch

The construction sequence for some elements such as a batch of floor slabs in the same story is not easy to identify. Those lifting components are grouped together if the order of the erection of these elements is not as important. The installation of those elements is normally flexible and determined by the site engineers. For safety reasons, the erected module should not obstruct the next one. Thus it is obvious that the control parameter is the angle formed by supply point, crane location and the installation point. The bigger this angle is, the sooner the lifting module has to be installed. Furthermore, when the two lifting modules have the same slewing angle, the further module is installed first. For example, this is illustrated in fig. 3.1 for 4 lifted modules, D1-D4.

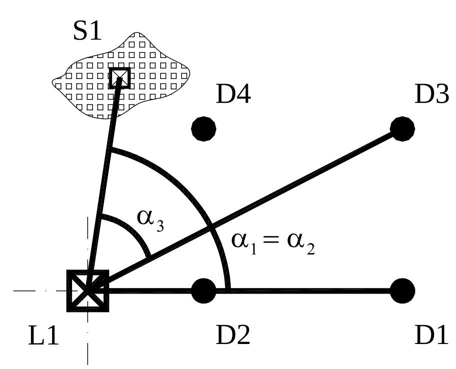


Figure 3.1: Lifting Sequence in a Small Group

The slewing angle is not the perfect criteria to determine the erection sequence between small groups. However, it still reduces the possibility of obstruction. It is also learnt from the real site practice that, this proposed safety erection sequence is more useful with the installation of vertical structures (e.g. columns and walls) than with that of horizontal precast structures (e.g. slabs and beams).

3.1.5 Safety Aspect – Control of Tower Crane Collision

Safety has been the constant watchword of the construction industry as it is one of the most accident-prone industries. A crane accident may cause the loss of lives, injury to people on site, failure of the crane itself, damage to properties and change the work schedule and thus can affect heavily all the stake holders such as the contractor, crane provider etc. It is necessary to assure safety when using cranes in particular and using heavy machines in general on construction sites.

Although tower cranes seem to be safer than mobile cranes, there are still reports of tower crane accidents. Main causes of those accidents can be classified as follows:

1. Equipment: i.e. the crane and its accessories;
2. Environment: i.e. the construction site; and
3. Operation: i.e. during crane operating activities including human errors

Crane accidents related to defects of equipment can be prevented by regular inspection and good maintenance plans, as well as by the proper use of the equipment itself (e.g. strictly following the load capacity chart). The construction site may cause crane accidents such as collapse due to unstable foundations, crashing of crane with neighbourhood obstructions such as nearby existing buildings, trees, elevated railway etc. Such accidents may be partly controlled by proper planning during which the practitioner considers all aspects related to crane usage as discussed in the previous sections. This study focuses on those crane accidents related to its operating activities. It is possible to argue that safety in tower crane usage may be obtained by forestalling (i.e. dealing with ahead of time) all possible collisions during the hoisting activities.

3.1.5.1 Classification of Collisions between Tower Cranes

The interferences between tower cranes may be classified as "*direct*" or "*indirect*" collisions. "*Direct*" collisions mean the physical crashes between the tower crane's components themselves. The most likely *direct* collisions between tower cranes may happen between the booms of the tower cranes; or between one tower crane boom and other tower crane mast.

The "*indirect*" collisions are other crashes between two tower cranes during their operations. The most significant *indirect* collisions may happen between:

(1) The lifted modules (and their associated lifting system i.e. the spreader beam, trolley, pulley, cables etc)

(2) The lifted module (and its associated lifting system) and other tower crane components when the crane(s) is/are in operations.

Other types of collisions between one tower crane itself with other obstacles on site (such as an existent building, or a tree, etc) are considered in section 3.1.1.

3.1.5.2 Previous Approaches to Control Collisions between Tower Cranes

Perhaps one of the first discussions about tower crane collisions is found in the work of Gray & Little (1985). The authors mentioned direct collisions between two saddle-jib tower cranes, where the horizontal jib intersects the mast of another crane, or the jibs clash. They suggested that these potential problems could be guarded against by setting the jibs at different vertical heights with a minimum of 4m between them, or 11.5m if one jib over sails the other's masthead; and by restricting the mast of one tower crane to be outside the radius of the other tower crane(s). Indeed those suggested numbers are depending on crane type. If the lower tower crane is a flattop saddle jib tower crane [*3.2*], the jib height difference of the two cranes can be as small as 4 meters. If the lower tower crane has a mast head above the boom to suspend pendants, the jib height difference of the two cranes can be as much as 11.5 meters, depending on how high its head truss on top is. It is also recommended to consider the deflection of the free-standing mast, which can be expected to be in the range of 2 to 4 meters, depending on the height of the mast and size of the load.

The problem of indirect collisions has been discussed in detail in the work of Zhang et al. (1999). The authors have attempted to solve the collision problem between tower cranes in their overlap area by minimizing the conflict index (NC) during the task-grouping process. Although this research has a few limitations (as will be pointed out later) it is the most systematic investigation of the matter. Following is a summary of Zhang's approach to take conflict into account.

First, the author defines $n_{ij,kl}$ as the number of intersections of the two triangles, of which apexes represent the crane location, the supply point, and the demand point, for example, $n_{ij,kl}$ = 0, 2 and 4 as illustrated in fig. 3.2 (a), (b) and (c) respectively. Then, the conflicts between cranes i and k can be represented as:

$$NC_{ik} = \sum_{l=1}^{L} \sum_{j=1}^{J} n_{ij,kl} \left(Q_{ij} + Q_{kl} \right) \tag{3.1}$$

Where Q_{ij} and Q_{kl} are the number of lifts of j^{th} and l^{th} task groups.

The conflict index (NC) was introduced for all cranes and all tasks to reflect the general possibilities of conflict and calculated as $NC = \sum_{i=1}^{I-1} \sum_{l=i}^{I} NC_{ik}$ (3.2)

[*3.2*] The most popular configuration of saddle jib tower crane designed by Comedil Cranes Company since 1998 (International Construction, 1999). Their flat-top character of boom/jib can help to save up to 6 meters vertical clearance between tower crane booms (Dieleman, 2002).

Obviously, the conflict index is closely related to the task assignment policy (to assign lifted jobs to multiple tower cranes). This task-grouping process can affect the total hoisting time of the group of tower crane. The authors thus build a "task assignment algorithm" to find a satisfactory solution that can minimise both the total hoisting time and the conflict index. However, the model of Zhang et al. has some limitations as described below.

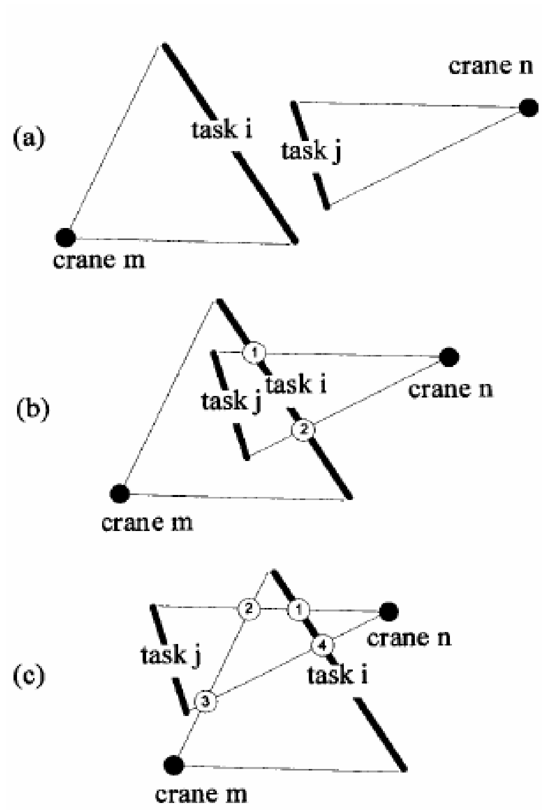


Figure 3.2: Severity of Conflicts (Extracted from Zhang et al., 1999)

1. It does not indicate the true possibility of conflict since it does not take the true boom length of the tower crane into account.
2. The possibility of conflict calculated according to the number of intersections is not quantitatively exact. For instance, in any case of possible conflict of the same number of intersection points, there will be the same conflict index. The possible conflict should be calculated in the way that it reflects well the effects of the size of overlap area.
3. The possible conflict according to the actual time was not considered and that the estimation of conflict solely bases on the overlap area is not correct since there are many cases, when the two cranes working on the overlap area in different period of time thus there should be no conflict.

Thus, a "more precise" approach to control tower crane's collisions is proposed.

3.1.5.3 Control the Collision between Two (Saddle-Jib) Tower Cranes

The crane layout planning can prevent both the "direct" and "indirect" collisions between tower cranes.

(I) Control Direct Collision:

The direct collision between the two booms of hammerhead tower cranes can be resolved by jacking up the booms at two different height levels as suggested by Gray & Little (1985). In the case of inevitable overlap of crane working area, when the tower crane's mast(s) lie(s) within other crane's working zone, the collision between a boom and other tower crane's mast can also be controlled in this manner, or/and by introducing safety switches that limits the boom angles within it own working zone. Fig. 3.3 illustrates how possible collisions between a tower crane jib with other crane's mast can be prevented by the two mentioned methods.

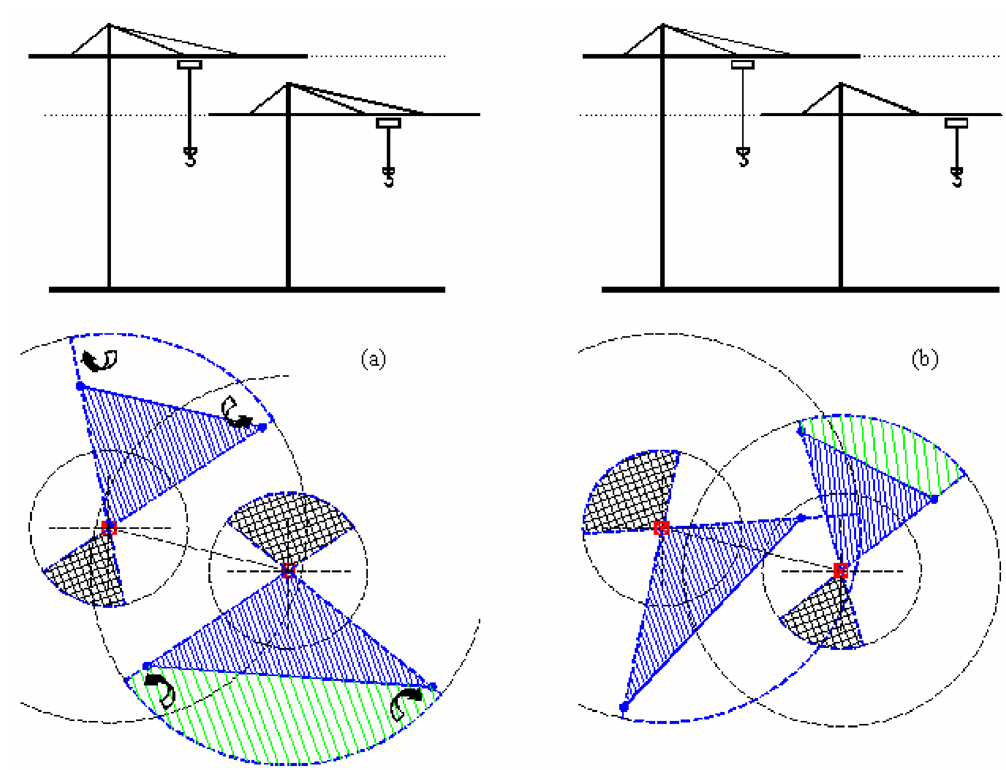
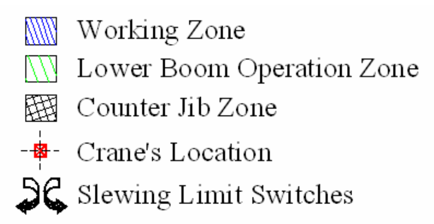


Figure 3.3: Control Collisions by (a) Using Switches (b) Levelling Jibs at Different Heights

Where the area denotations are as below



To control the direct collision possibility by setting jibs at different heights, it is necessary to determine which tower crane jib should be set at higher level. There are a few criteria to decide the height level of each crane to control direct conflict. One of the criteria is the role of crane in the assembly/dismantling procedure. The last crane takes part in those procedures should be the highest among them (since it should be able to help dismantle other cranes). The other factors investigated are the relative horizontal distance between the two crane locations and their length of booms; and more importantly, the working zone of each crane.

(II) Control Indirect Collisions

Before calculating the possibility of indirect collisions, it is necessary to ensure that the direct collision of a tower crane and other crane’s mast is prevented, or none of the cranes be located in the other crane’s safe working zone. In such ideal situation, the *indirect* collision hardly happens. *Indirect* collisions between tower cranes can occur where there is an overlap in the working area of the two, or where a component of a tower crane such as the boom, or the counter-balance boom may violate the working zone or may impede the proper activity of other crane.

In fig. 3.4.b below, there is no overlap area according to Zhang et al. However, the boom of lower tower crane can violate the working zone of the higher crane, and thus may cause indirect collision according to the new collision concept proposed in this thesis. Moreover, collision might never happen if the two cranes operate their jobs in different time periods. Therefore, the “true” possibility of indirect collision between two cranes must address the two conditions: (1) Existence of overlap working zone, and (2) Existence of overlap operating time, when they perform the lifting jobs. If the two conditions above are satisfied, then there is a possible collision between the two cranes. This possible collision makes it difficult for the two cranes to perform their task in the estimated time. In fact, since the crane operator(s) have to watch out the other crane activities to ensure safe rigging in the overlap working zone, it usually takes longer time than it should be if there is no possibility of conflict.

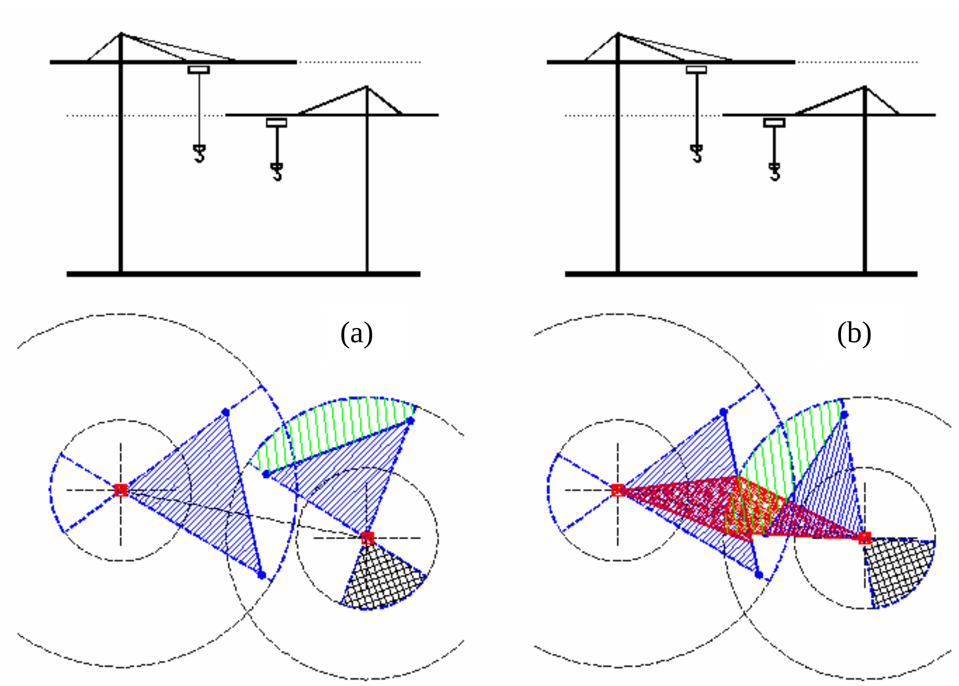
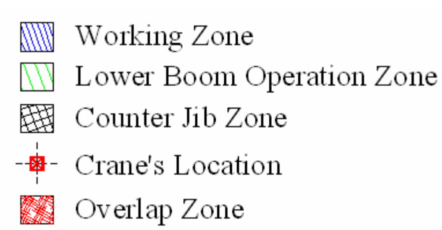


Figure 3.4: Possible Indirect Collision Recognition
(a) No Collision (b) Possible Collision

Where the area denotations are as below



Thus, the method of controlling collision is proposed as below: If the two cranes perform in the overlap working zone at the same time, either one of them has to postpone its activities until the area is clear and safe for its operations. The delay time will be counted based on the "actual period of time" during which both the cranes operate within overlap area, as well as based on the proportion of overlap area and the total working zone for each crane.

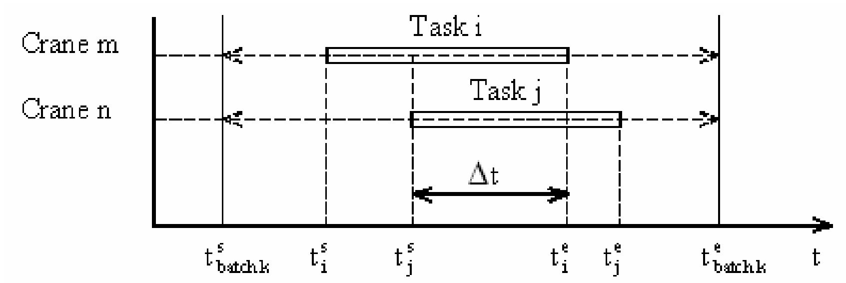


Figure 3.5: The Overlap Time

Where:

t^s_{batchk} : Start Time of Batch k (Start Time of the First Task in Batch k).

$t^s_{i,j}$: Start Time of Task i, j in Batch k Respectively.

t^e_{batchk} : Finish (End) Time of Batch k (Finish Time of the Last Task in Batch k).

$t^e_{i,j}$: Finish (End) Time of Task i, j in Batch k Respectively.

Note: The Tower Cranes Perform Task i & Task j Have Overlap Working Zone.

As shown in fig. 3.5, possible collision of the two cranes can only happen in the period of time Δt. Δt is called the overlap time.

Further investigation shows that, the crane, which has boom at a lower level, may cause indirect collision (by its physical dimension of the boom and counter-balance boom when operating in the overlap area) with the lifting modules of the higher crane. This finding leads to a different approach to calculate the actual overlap area for each crane as follow.

For the higher crane, the total working zone area is the area of the triangular $O_mA_mB_m$ and overlap area is the area of the triangular $O_ma_mb_m$ (see fig. 3.6).

Therefore, the delay time of crane m should be:

$$T_m^{delay} = \frac{S_{Oab}}{S_{OAB}} \Delta t = \frac{a_m b_m}{A_m B_m} \Delta t \qquad (3.3)$$

For the lower crane, the total working zone area is the area bounded by the angle $\angle O_nA_nB_n$ and overlap area is the area bounded by the angle $\angle O_na_nb_n$ (see fig. 3.7). Therefore, the delay time of crane n should be:

$$T_n^{delay} = \frac{\gamma_{OAB}}{\gamma_{Oab}} \Delta t \tag{3.4}$$

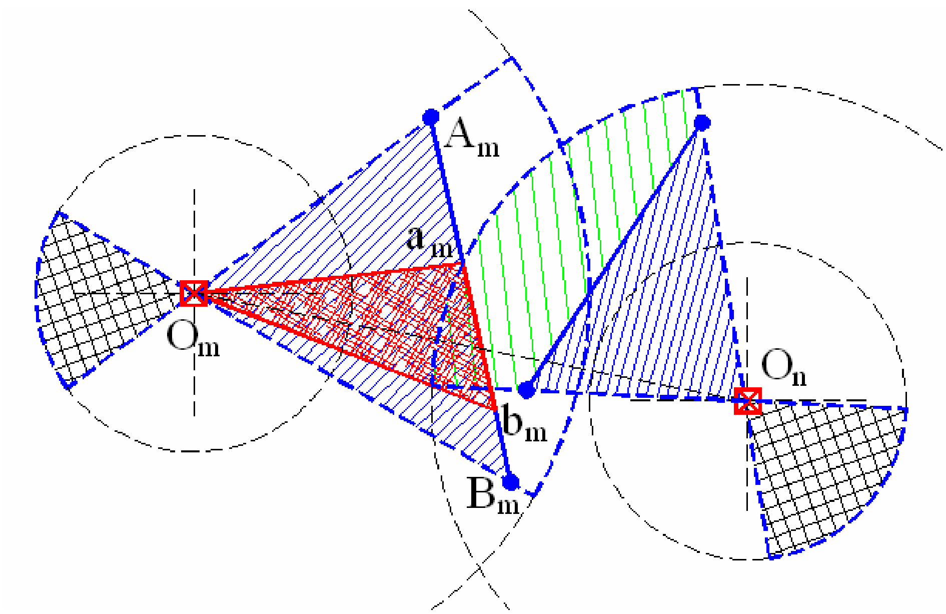


Figure 3.6: The Working Zone and Overlap Area of Crane m (The Higher Crane)

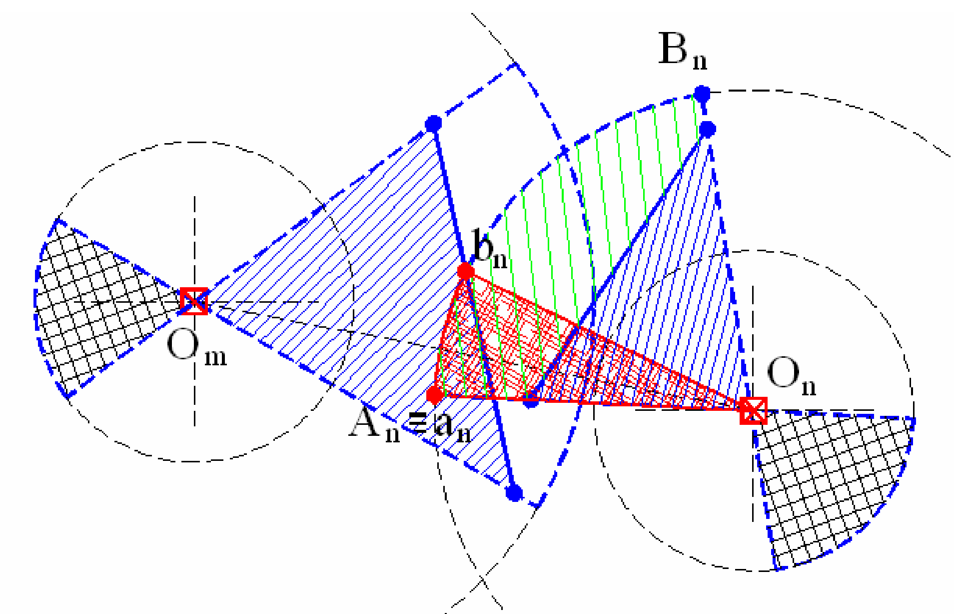
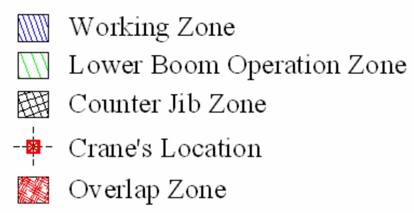


Figure 3.7: The Working Zone and Overlap Area of Crane n (The Lower Crane)

Where the area denotations are as below



3.2 Overview of the Proposed Program for CLP

As presented in the previous sections, CLP are very complicated and relate to many problems of real practices. A computer program called I-LIFT is developed to solve CLP and eventually raise productivity and safety of lifting work in construction project. Due to the complicated nature of the problem, a successful program must address how to interact with experienced user(s). I-LIFT enables positive interactions with experienced users (see fig. 3.8 and 3.9) to overcome the common disadvantages of computer models about simplifications and being irrelevant to real practice (as pointed out by Shapiro, 1999).

The I-LIFT program composes of two main parts, namely the Pre-Process Algorithms Module (PPAM) and the Optimisation Module (OM). The figure below presents the outline flowchart of the I-LIFT program for CLP.

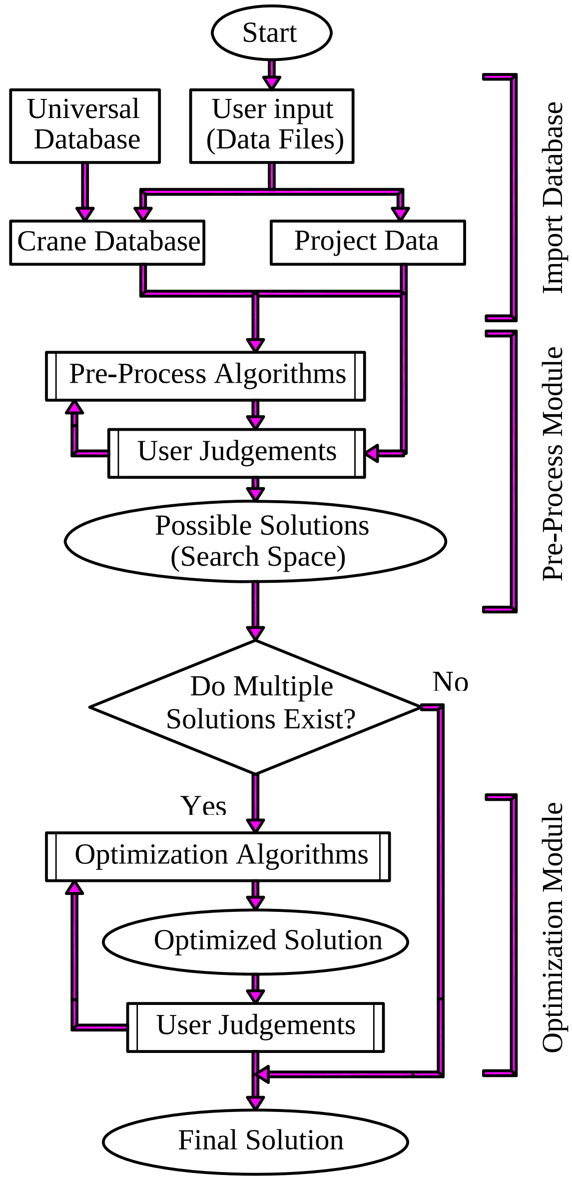


Figure 3.8: Flowchart of I-LIFT Program for CLP

3.2.1 Pre-Process Algorithms Module (PPAM)

PPAM is aimed to help novice practitioners to solve CLP in a step-by-step procedure. The expected results of this module are the feasible solutions for CLP (this is also the search space of CLP of OM). The PPAM is related to real site experiences with the practical constraints involved. A final solution for CLP can be obtained in this part of the program if there are no multiple solutions available. In this case, there is no need to use the Optimisation Module. However, this simplified situation hardly happens in larger real site projects, especially when multiple cranes are used. The PPAM usually ends up with a number of possible solutions for the considering project. The flowchart of PPAM is shown in fig. 3.9.

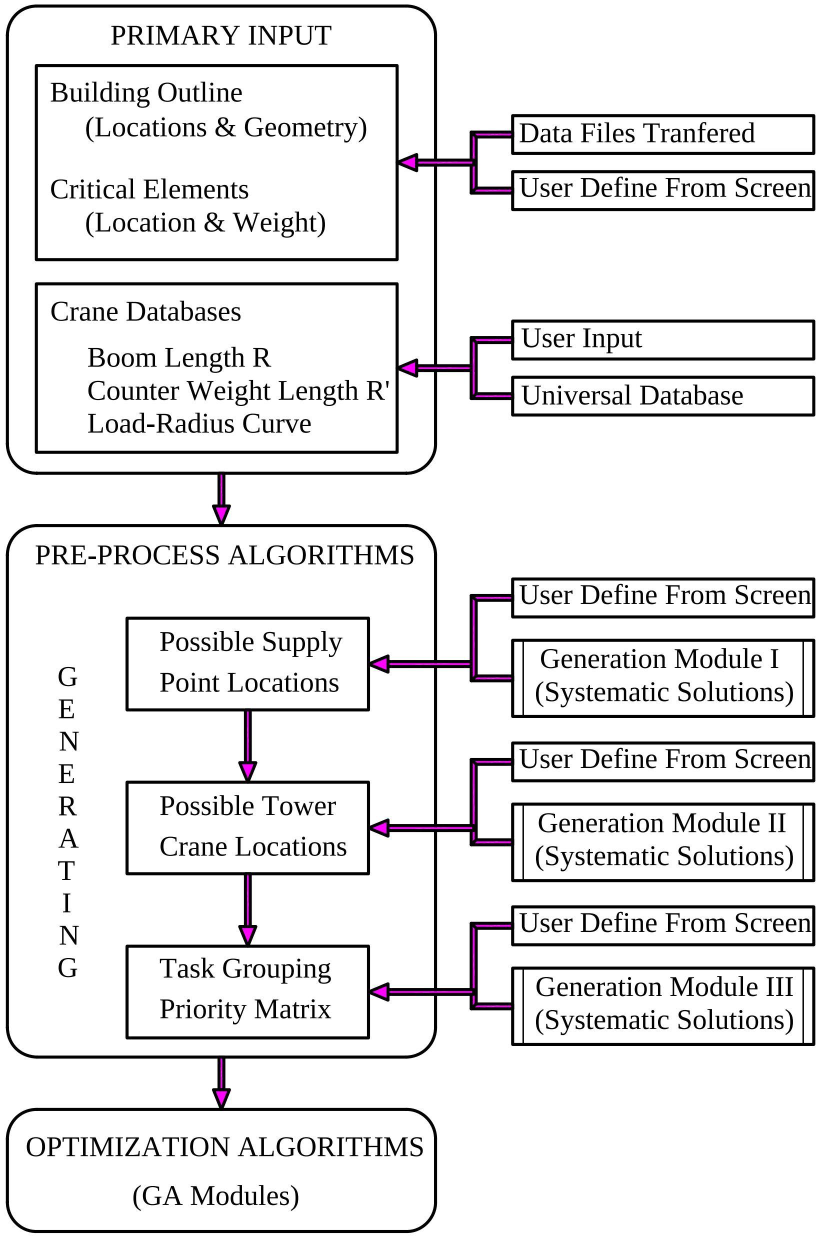


Figure 3.9: Flowchart of Pre-Process Algorithms Module (PPAM)

As shown in fig. 3.8 and 3.9, user interactions play a very important role in the I-LIFT program, especially in the PPAM, where the experiences of practitioners can be of utmost usefulness. The flowchart of the program also shows the privileges of expert users. He can decide where the possible location for cranes, supply points locations etc. without the need of the generation modules or he is able to verify the possible solutions generated from these generation modules, reject or add other solutions from his own experience with consideration of other characteristics of the project.

3.2.1.1 Define Possible Locations of Tower Crane – Generation Module I

The main part of the PPAM is the Generation Module I that aims to generate feasible areas where the tower crane may locate. This module is illustrated in fig. 3.10.

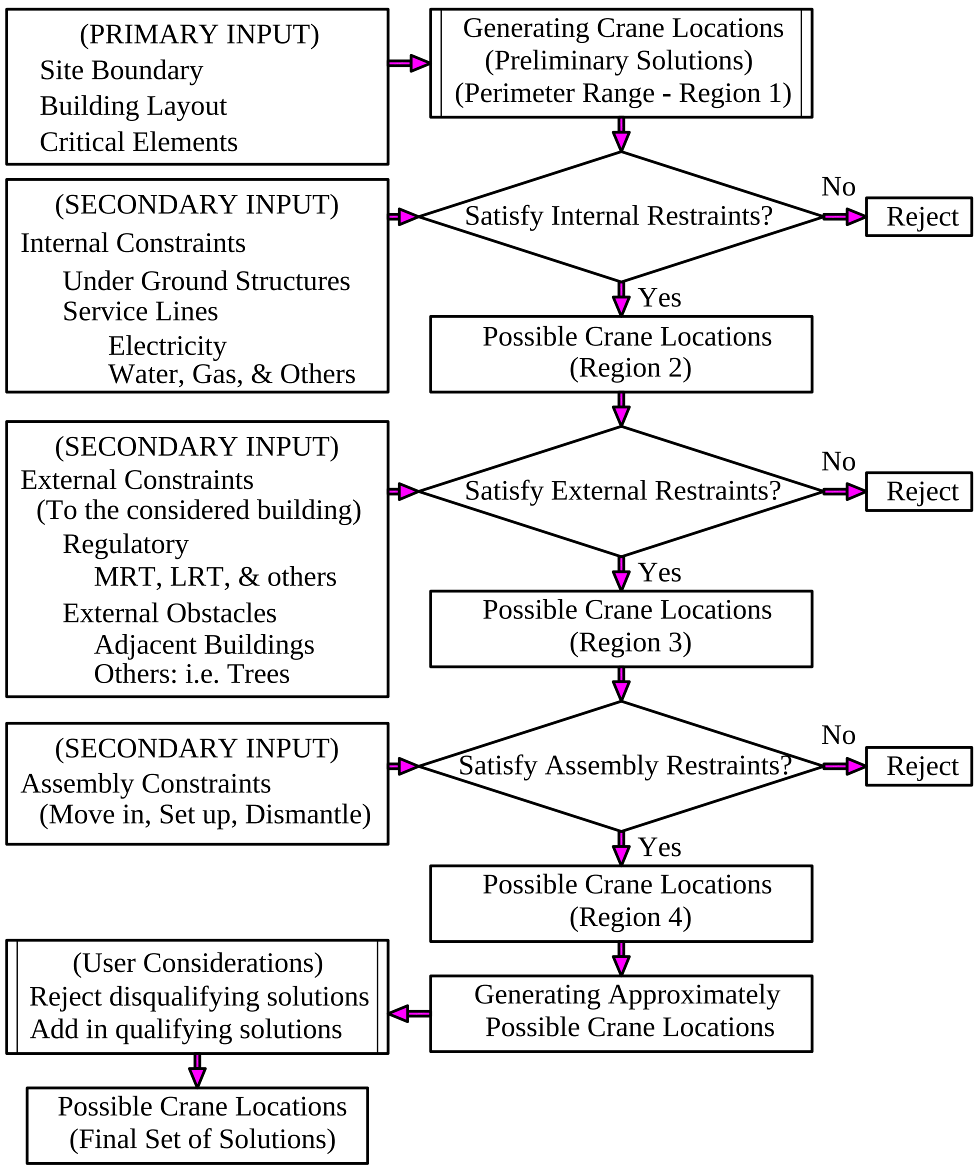


Figure 3.10: Flowchart of Generation Module I – Possible Crane Locations

3.2.1.2 Define Possible Supply Point – Generation Module II

Another part of the PPAM is the Generation Module II that aims to generate feasible areas where the resources such as precast lifting modules, steel bar, formwork etc. may be stored, prepared and delivered. The expected outcome of this generation module is the possible locations for supply points. The flowchart of this module is illustrated in fig. 3.11.

Perhaps the most important factors to consider using an area as a supply point are its location and its available space. These two factors impose considerations relating to the accessibility and the spaciousness of the supply points to ensure smooth transportations on site as well as preventing double handling due to the lack of space at supply point. In addition, the location of a supply point in CLP needs further considerations. Since the supply point is aimed to deliver resources for the tower crane(s), its location should be chosen to support the crane activities. Location of supply points can help ensure the continuous operations of the tower crane. Supportive supply point locations help to reduce double handling, thus enhance the efficiency of the crane work.

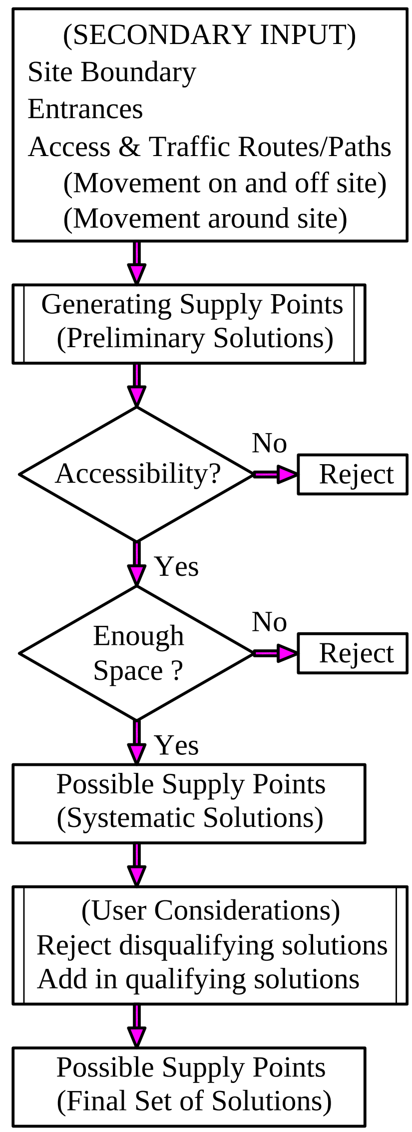


Figure 3.11: Flowchart of Generation Module II – Possible Supply Point Locations

3.2.1.3 Task Grouping and Installation Priority

This section introduces the general flowchart to group lifting elements into small groups. There are three main groups of factors to consider, namely Crane Capacity, Geometry and Construction techniques as discussed in section 3.1.3.

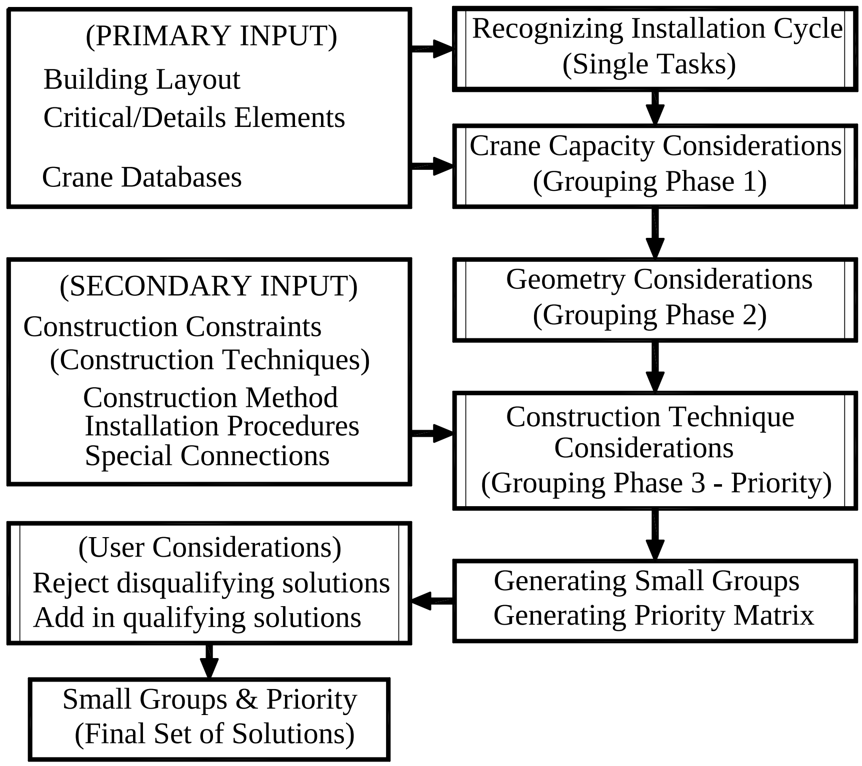


Figure 3.12: Flowchart of Generation Module III - Task Grouping & Installation Priority

3.2.1.4 Database and How to Handle Data

The Database for any CLP includes Project Database (PD) and Crane Database (CD). PD consists of the information about the project itself such as the site boundary and constraints, the building to-be with key structural elements as well as information about the construction technology and other considerations. CD stores the information about available cranes that can be used in the project. CD might be imported from the Universal Database that contains the information of company or available cranes. Practitioners can update CD by introducing new cranes from the program's templates.

3.2.2 Optimisation Module (OM)

As mentioned in section 3.2, the OM is applied to choose the optimal solutions from a number of possible solutions generated from the PPAM. The OM is a "brave" attempt to tackle the extreme difficulties of CLP quantitatively. The OM is especially useful for large projects where multiple cranes are used. Associated with its difficulties, challenges and rewards, the OM becomes the focus of this study. Attempts have been made to build a computer model to evaluate the alternative solutions of CLP to select the best solution that helps to obtain higher efficiency of the lifting work and other associated factors such as time, tower crane cost, safety in installations etc. Detailed objective and expected outcome of the model are described in the next section.

3.3 Computer Model for CLP

It is ambitious that a computer model can be successfully built to solve the CLP. This section is to provide the objective and scope of the model for CLP as well as to emphasize the promising outcome of the model.

3.3.1 Objective and Scope of the Model for CLP

The model is aimed to solve the complexities of site layout planning, where tower crane work governs other site planning activities. More specifically, the computer model for CLP should be able to choose the best location for crane(s) and supply point(s), to produce the most efficient policies to assign lifting modules to supply point and the lifting task to crane so as to minimize the total hoisting time (as well as renting time) of the crane(s) for a construction project.

The current scope of the model is optimising the use of tower cranes in the installations of structural precast concrete components of high-rise buildings.

3.3.2 Expected Outcome of The Model

The CLP model is expected to be able to find the most suitable solutions among the possible alternatives with quantitative reference of hoisting time and/ or other associated factors such as crane rental cost, conflict possibilities etc. To be specific, the model should be able to

(1) choose suitable location(s) from possible locations of tower crane(s).

(2) select suitable supply point location(s) for tower crane(s) used. (i.e. each lifting module should be delivered from which supply point?).

(3) propose suitable assignment policy for group of tasks to tower cranes (i.e. which crane lifts which modules).

(4) propose a suitable number of cranes and suitable model of cranes from the database, a list of available cranes provided by the contractor company or extracted from the crane market.

(5) suggest a safe lifting sequence as well as control the possibility of collision between cranes.

Each sub-problem of those mentioned above from (1) to (4) is an NP-hard problem, especially in a large scale problem when either the number of tasks, or the number of possible locations of crane, or the number of supply points, or the number of available cranes is big. The first problem seems to be the central application of the model, to find the operating locations for the tower cranes. The second problem is to find supply point locations for tower crane. The tower crane locations and their supply points have close relationship as mentioned by Tam et al. (2001). This mutual interaction between supply points and tower crane locations was proved quantitatively in section 5.1.3. Tam et al. (2001, 2003) also built a GA model to optimise the tower crane locations and supply points at the same time. However, their model is very simple and thus has some major limitations. It works for single tower crane only, and does not consider different configurations of different tower cranes. In addition, their model applies for the conventional cast in-situ concrete projects since it does not consider the lift sequence. This study aims to build a more advanced GA model that can work for a group of tower cranes. Due to the presence of multiple cranes and multiple supply points in the same project, it is necessary to consider how to assign a single task to a tower crane and a supply point among the available ones (the third problem). In addition, when multiple cranes can be used, it is necessary to determine the suitable number of crane for a particular project. The GA model is upgraded during its development period, to consider different tower crane configurations. Hence, the most suitable tower crane model(s) can be selected from an available list in the database (problem 4). Because of their interdependent relationships, all of these sub-problems are solved simultaneously to reach the optimum solution. Thus, the overall expected outcome of the model is to solve the facilities site layout problem for tower crane(s). This study is eventually aimed to help practitioners to plan effectively for this lifting part in the defined stage of construction (i.e. the installation of structural pre-cast concrete components of high-rise buildings).

3.4 What Makes the CLP Hard?

Belonging to the facilities layout problems (FLP), CLP inherit the natural difficulties of this class of problem, as stated by Tommelein (1991) that (sic) no well-defined method can guarantee a solution. Although the facility layout obviously affects on money and timesaving, especially in large projects (Hamiani and Popescu, 1988), it has still probably been the most neglected fields in the construction industry, and the attitude of the engineers has been that FLP only can be solved as the project progresses (Handa and Lang, 1988 and Tommelein, 1989). In short, the CLP are inherently difficult due to the restriction of site constraints such as the location of the permanent facilities, and site topology as well as the requirements of satisfying a variety of competing and often conflicting design objectives (Hamiani and Popescu, 1988). The existence of many project stakeholders (contractors, pre-casters etc.) involved in a high-rise precast construction project makes CLP more complicated.

Mathematically, there are some difficulties associated with CLP, namely the scaling problem, the uncertainty and the dynamic nature of the problem, and the sparseness of the solution space discussed in detail in the following sub-sections.

3.4.1 Scaling Issues - The Size of the Problem

The size of a crane location problem can be approximated by the size of its components such as the crane location matrix, the crane assignment matrix, the supply point matrix, and the crane database matrix. Those matrices contain the information about resources (tower cranes, storage and delivery points, lifting elements), where they locate and how many of them. Further indications of those components of CLP refer to specific configurations of available tower cranes, the weight of each lifting module and their order of installation (that relates to timing and scheduling). A rough approximation of a problems size can be given by the product of how many lifting tasks must be completed and by how many tower cranes. In addition, the search space is also formed by the number of possible locations for tower crane and the number of available tower cranes (from the database) that are usually more than the number of tower cranes actually used for the project. The following example is to demonstrate the problem of scaling, or how huge the search space of CLP can be even with a small dataset. A project is assumed to have a data set of 10 possible locations of tower cranes, 5 possible locations of supply points, 10 tower cranes available in the database, 100 lifting modules. There will be three tower cranes used in the project. There will be (10*9*8) possible scenarios to locate 3 cranes into 10 possible locations, (10*9*8) possible scenarios to choose 3 cranes out of 10 cranes in the database, (100^3) possible scenarios to assign 100 lifting modules to 3 cranes, (100^5) possible scenarios to assign 100 lifting module to 5 supply points. Eventually, there will be $(10*9*8)^2 * (100^8) = 5184*10^{18}$ possible solutions! This is a search space with gigantic proportions such that no advanced search techniques even with the aids of supercomputers can guarantee to find the optimum solution. Efforts have been made to minimize the search space of CLP such that it can be explored with the aids of a normal computer in a reasonable time. One of the most effective methods that contribute to the matter is the introducing of task grouping concept. Without loss of much generality, lifting modules of the same type and lifting order, relatively close to each other in terms of installation locations such as in the same part of the building (of the same floor) are considered as one lifting unit, i.e. handled by one crane and stored at the same supply point. This assumption is reasonable in real site practice because it is indeed compliant with the zone work concept of tower crane [*3.3*] and the fact that many lifting modules, which are installed in the same small region, are usually delivered at the same nearby supply point (or storage area). The grouping method can greatly narrow the search space. For instance, with the same example above, but the 100 lifting modules are grouped into 20 small groups (i.e. 5 times smaller). The search space is $(10*9*8)^2 * (20^8) = 5184*256*10^{10}$, being reduced 390625 times! However, the challenges pertaining scaling matter of the CLP still remain. Further reduction of the search space can be obtained by improving the model to a higher degree of allocating resources that is mentioned in section 6.3.

[*3.3*] Contrary to mobile cranes that are able to serve wherever location that is accessible, static base tower cranes stay still at a position on site and thus can serve only the lifting jobs within the area limited by its boom length. This area is called the working zone of the crane.

3.4.2 Uncertainty and the Dynamic Nature of Real Problems

Practically speaking, finding an optimal site facility layout plan is often less difficult than coping with uncertainties during the planning process and unpredictable disturbances during the installation. Like other real world problems, CLP is subjected to various possible changes during its execution. These changes may affect the total schedule of the plan, either resulting in disturbances for the lifting plan or turning it into a completely new plan. They may be caused by a mechanical failure, human error, or severe weather. For example, the cranes may break down and need to be replaced, the location of supply point locations may change during the construction, the supply plan of supplier may be delayed due to some unfavourable situations, and the lift order may change to adjust to onsite situations. Such changes may require either only the replacement of a single resource, or the complete reformulation of the plan.

3.4.3 Infeasibility - Sparseness of the Solution Space

Depending on the representation scheme and the customized genetic operators, there would be always feasible solution generated during GA iterations. However, it is not guaranteed that these solutions satisfy the constraints of the CLP such as the crane has enough capacity to lift the heaviest element (in the relative reach) or its boom length is long enough to reach the farthest element. Thus, there may be no solution for the CLP. In this case, the model will inform user by a message that says, for example "Cranes lack of capacity. Please consider higher capacity cranes in the database" if all the cranes are not able to handle the load.

Other considerations are about the constraints of CLP. To ensure the correctness of the obtained solution, one has to check other constraints of the problem, such as the crane capacity, the boom length, or the total completion time etc. Those constraints indeed make the search for an optimal solution more difficult by breaking up an otherwise continuous search space. When many constraints are added, traversal of the search space is confounded. This can be illustrated by the fig. 3.13 below.

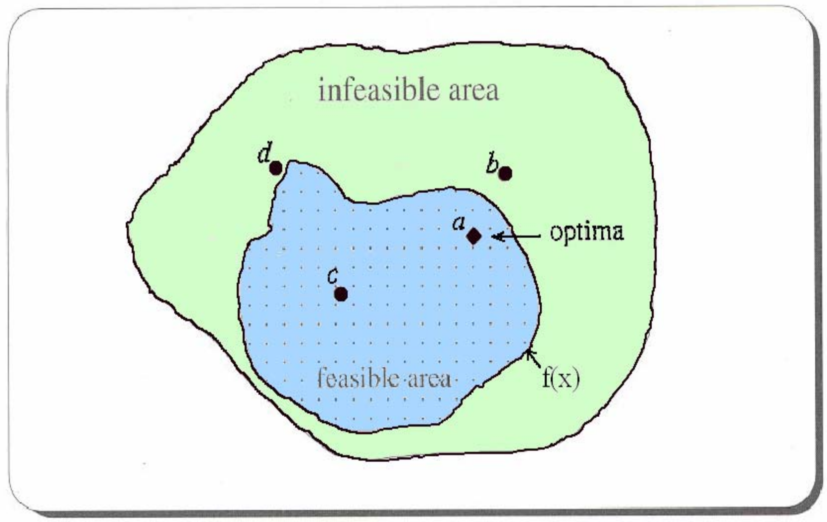


Figure 3.13: Solution Space: Feasible Area and Infeasible Area (Adapted from Gen and Cheng, 1996)

It is assumed that a constraint f(x) separates the search space into two regions: feasible and infeasible one. In fig. 3.13, it can be expected that 'b' contains much more information about optima than 'c' even though it is infeasible. However, since 'b' violates the constraint, it must be rejected while 'c' may survive and continue to reproduce its genes. Supposed 'c' might be the best one found so far, and then GA most likely continues their search around 'c' and thus be misleading of where the optimum may lie. If the constraint f(x) does not exist, since 'b' is nearer to the optima, it may have better fitness compared to 'c'. If GA searches around 'b' rather than 'c', it may find the optimum faster.

3.5 Assumptions of the Model

The OM is based on some assumptions as mentioned below.

- Geometric layout of all possible supply points, crane locations, and installation locations of lifting modules are pre-determined, fixed and denoted by points. That is, the OM works on the feasible solutions generated by the PPAM.
- The supply points are assumed to have enough space to store the amount of lifting modules for the tower crane(s) to operate continuously as planned.
- One lifting job is continuously delivered by one tower crane only, from one supply point to its installation position.
- The installation order of all precast lifting elements is assumed to be in batches. For each batch, one type of fabricated module is installed at the same level. The starting time for installation of a new batch must be after the completion of the previous batch of modules. For example, the installation of the batch of precast beam in the 2nd floor must be await the installation of the batch of the columns in 1st floor.

CHAPTER IV: IMPLEMENTATION OF CLP USING GA

4.1 The Rationale of Using GA for CLP

Continuous variable problems are often formulated and solved using mathematically based optimisation methods. These methods typically become impractical when faced with problems of significant size or with the large sets of constraints. For the discrete variable problems, the mathematically based optimisation methods are usually not applicable since the conversion from discrete to continuous variable problems often results in very efficient solutions and this conversion even may not be warranted for certain problems. Furthermore, in many problems, computation of gradient information usually needed for continuous variable problems is difficult or impossible to obtain. Therefore, the stochastic search techniques have become popular methods to solve discrete variable optimization problems. The Genetic Algorithm (GA) is an evolutionary algorithm based on Darwinian survival of the fittest theory. GA has found significant use in solving optimization problems with discrete variables and complex cost and constraint functions.

Belonging to the class of NP-hard combinatorial problems with discrete variables, CLP is extremely difficult to solve. The motivation for using GA for CLP is due to the "globality", parallelism and robustness of GA. It is the author's strong belief that, with their flexible genetic mechanism of potential genetic operators, GA is capable of dealing with the non-convexity, locality and complexity of CLP. In addition, GA is simple and powerful in their search for improvement, and not fundamentally limited by restrictive assumption about the search space. In fact, since the 1980s, GA has been applied to solve NP-hard combinatorial problems. Many successful applications of GA have been reported in a great number of real world optimization problems such as distribution pipeline system, TSP, allocation of funds to projects, scheduling, handling of materials and so forth (Chambers, 2001). These results reinforce the belief that using GA is a good choice for CLP.

4.2 Implementation of the GA Model for CLP

In order to build a successful GA model for CLP with the expected outcome as discussed in section 3.3.2, the CLP is required to reflect the relationships between tasks (lifting sequence, priority etc.), and resources (tower cranes library, supply points, lifted elements and possible crane locations). More specifically, the solution should contain information on how to locate a crane among possible locations, to present a chosen crane from the list of available cranes, to assign a lifted module to the chosen crane(s) and to provide the lifted module from a possible supply point location. Other considerations include the decision on the number of cranes to be used, definition of the lifting sequence of lifted tasks, and method to control possible collisions when multiple cranes are used. These matters will be considered when building the objective function of the program in the latter section.

Building a GA model for CLP includes encoding the representation of a solution, customizing the genetic operators that work with the representation scheme and building the objective functions of the GA model.

4.2.1 Encoding of a Chromosome - Representation Scheme

Since there are many different schemes of genetic representations, choosing a suitable representation scheme for CLP is not a simple task. Generally, for any genetic algorithm, the representation should be a minimal, complete expression of a solution to the problem (Wall, 1996). It is wise to choose the representation scheme that is able to eliminate non-feasible solutions, thus narrowing the search space to the minimum.

Jaramillo et al. (2002) provided a valuable lesson of using GA to solve general location problems with the use of the binary-bit-string representation. Most of GA applications have employed this most basic form of representation. For the special CLP, the author has chosen that simple representation accompanied with customized genetic operators. Although the traditional binary string might be the simplest form of genetic representation, it is indeed good enough for the location problem since the two-state bit can well indicate the information needed about the state of a single facility or an allocation decision making (yes or no). For a single NP-hard problem such as TSP, the integer representation might be better than the binary bit string representation since it results in a shorter chromosome. However, the CLP is a combination of four assignment problems (see section 3.3.1 and 3.3.2) and it is difficult to create an integer representation with four different allele sets. Hence, the representation of chromosomes in a GA model takes the form of binary bit strings with customised genetic operators to enhance the efficiency of this basic form of representation. Each locus in the chromosome has two possible alleles: 0 and 1. The chromosome of CLP contains information about the possible location of tower crane(s), the possible supply point for each lifted task, the task assignment to crane chosen in the database. Consequently, different information is encoded into different groups of bit string (genes) called Crane Location Gene (CLG), Supply Point Gene (SPG), Crane Assignment Gene (CAG), and Crane Database Gene (CDG) described in further detail in the following subsections.

4.2.1.1 Crane Location Gene (CLG)

Crane Location Gene (CLG) is a group of genes that contains the information about possible location of crane(s). Each possible location of a crane is represented as a single bit with value of 1 if the crane is located at that location or with the value of 0 otherwise. For each crane, it needs a group of genes to indicate the information about its location. For instance, the string of 00100 denotes that the crane is located at the third possible location among five possible crane locations. The length of each group of CLG is $N_{location}$. The total number of groups of CLG is N_{crane}.

4.2.1.2 Supply Point Gene (SPG)

Supply Point Gene (SPG) is a group of genes that contains the information about the possible supply point locations that can be chosen to be the delivery point of lifted elements. Each possible supply point location is also represented as a single bit with value of 1 if the lifted element is delivered at that supply point location or with the value of 0 otherwise. For each lifted task, it needs a group of genes to indicate the information that the lifted element is supplied at a supply point location among the possible ones. The length of each group of SPG is N_{supply}. The total number of groups of SPG is N_{small_group}.

4.2.1.3 Crane Assignment Gene (CAG)

Crane Assignment Gene (CAG) is a group of genes that contains the information about assigning a task to a crane (the crane is chosen to perform the lifted task). Each crane assignment gene is also represented as a single bit with value of 1 if the crane is chosen to perform the task or with the value of 0 otherwise. For each lifted task, it needs a group of genes to indicate the information that which crane (among the used ones) lifts the lifted element. The length of each group of CAG is N_{crane}. The total number of groups of CAG is N_{small_group}.

4.2.1.4 Crane Database Gene (CDG)

Crane Database Gene (CDG) is a group of genes that contains the information about available cranes that can be used in the project. Each CDG is also represented as a single bit with value of 1 if the crane is chosen or with the value of 0 otherwise. For each crane, it needs a group of genes to indicate the information about the crane chosen among the available ones in the list. The length of each group of CDG is $N_{available}$. The total number of groups of CDG is N_{crane}.

4.2.1.5 The Overall Chromosome of CLP

To summarise, the general structure of a chromosome for CLP is described as in figure 4.1 below

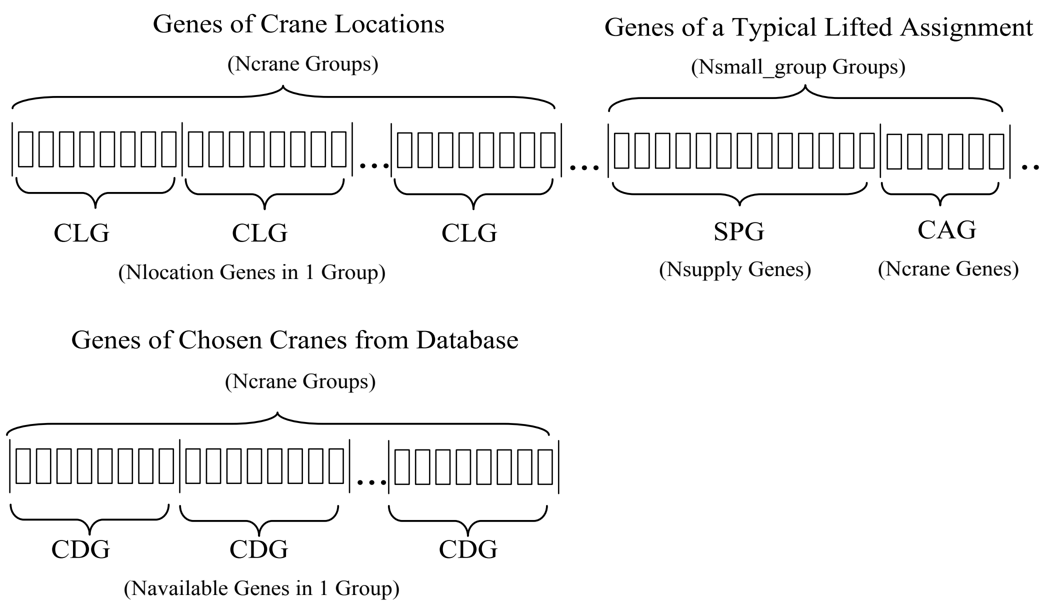


Figure 4.1: General Structure of the CLP Chromosome

The total length of a typical chromosome in binary string representation is calculated as $L_{binary} = N_{crane}*N_{location} + (N_{supply} + N_{crane})*N_{small\_group} + N_{crane}* N_{available}$ (4.1)

Since the GA operators work with permutation encoding (section 4.2.4), the chromosome is transferred to integer representation in which each group of genes is presented by an integer number. The total length of typical chromosome in integer representation is calculated as $L_{integer} = 2*(N_{crane} + N_{small\_group})$ (4.2)

The number of $(2*N_{crane})$ refers to the information of how to locate the cranes in possible locations and how to choose these number of cranes from the crane database. The number of ($2*N_{small\_group}$) refers to the information of how to locate these lifted modules to possible supply points and how to assign them to the cranes used. $L_{integer}$ is used to calculate the number of chromosomes in the evolving population (section 4.2.6.1).

4.2.1.6 Problems of the Binary String Representation and Solutions

Unfortunately, it is soon discovered that the simple binary bit string representation has a possibility of creating non-feasible solutions. For example, a group of CLG for crane 1 can turn out to be 010010. That means crane 1 can locate at both location 2 and 5 at the same time. This is obviously impossible or the above CLG will result in a non-feasible solution. The simple binary bit string does not always represent the feasible solution effectively since it is prone to present the non-feasible ones. For instance, a simple group of genes of length 10 contains only 10 valid solution while it can generate of $2^{10} - 10 = 1024 - 10 = 1014$ non-feasible solutions. That means less than 1% of the generated solution is valid! More seriously, the non-feasible solutions increase the size of the search space and thus make the search more difficult. One possible solution is improving the binary bit string representation by a customized initialiser to generate only feasible solutions and by customized genetic operators that are able to create new and valid solutions through GA iterations (i.e. solutions satisfy all equations from 4.17 to 4.21). Those genetic operators make use of temporary arrays with permutation coding. Details of this approach can be seen in section 4.3.4 where customized genetic operators are presented.

4.2.2 Building the Objective Function of CLP

The mathematical model of the objective function is built to calculate the fitness function of each solution of the problems. For CLP, the objective function is to minimize the total hoisting time. The total hoisting time is counted for the installation of structural precast components. If multiple cranes are used, the total hoisting time is calculated as the sum of hoisting time of each crane from the beginning of the installation procedure until it finishes its last lifted job. The hoisting time of each crane may be different depending on the task grouping and the installation order of elements. The hoisting time model takes into account the following: the crane location, the supply point, and the demand point (this relates to the angular movement of the boom and the tangent movement of the trolley along the boom); the height of the installation point (this relates to the hoist movement of the hook); the configurations of each crane (the hoist velocity, the slewing velocity and the trolley movement velocity); the simultaneous movements of the boom and the trolley in the horizontal plane; the loading and unloading time; and the lifting sequence of lifted modules. Due to the uncertainty and difficulty when being estimated, other factors such as wind speed, operator's vision and the crane operator's experience are not considered in this model. It is also assumed that the weight and the dimensions of the load do not affect remarkably their hoisting time.

4.2.2.1 Model to Calculate the Hoisting Time of a Single Lift

The total hoisting time for each lifted module is calculated according to Zhang et al. (1999). Hook travel time for the n^{th} request:

$$T_{Hook}^{n^{th}} = T(D_{j-1},S_j) + T_L(S_j) + T(S_j,D_j) + T_U(D_j) \quad (4.3)$$

Where: $T(D_{j-1},S_j)$ is the hook travelling time from the last demand point to the supply point of n^{th} lifted assignment (without load). $T_L(S_j)$ is the delay time for loading at S_j. $T(S_j,D_j)$ is the hoisting time for lifted assignment n^{th} from supply point S_j to demand point D_j (with load). $T_U(D_j)$ is the delay time for unloading at D_j.

The hoisting time $T(S_j,D_j)$ is calculated in eq. 4.11.

Time for trolley radial movement:

If (XD_j, YD_j, ZD_j) and (XS_j, YS_j, ZS_j) refer, respectively, to the location of S and D of a task, for a crane located at (x, y), the distances between these locations are:

$$\rho(D_j) = \sqrt{(XD_j - x)^2 + (YD_j - y)^2} \quad (4.4)$$

$$\rho(S_j) = \sqrt{(XS_j - x)^2 + (YS_j - y)^2} \quad (4.5)$$

$$l_j = \sqrt{(XD_j - XS_j)^2 + (YD_j - YS_j)^2} \quad (4.6)$$

Time for trolley tangent movement:

$$T_a = \frac{|\rho(D_j) - \rho(S_j)|}{V_a} \quad (4.7)$$

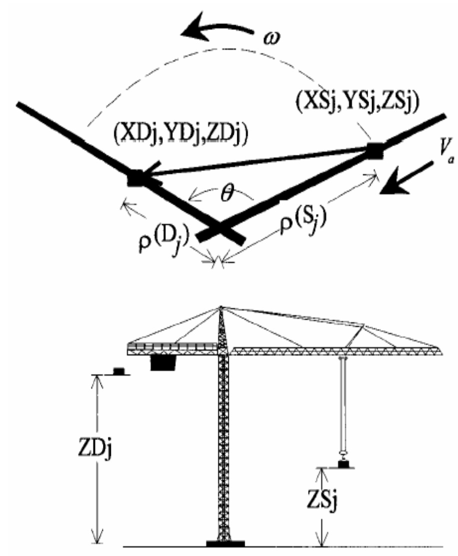


Figure 4.2: Model to Compute the Hook Travel Time (from Zhang et al., 1999)

$$T_\omega = \frac{1}{V_\omega} Arc\cos\left(\frac{|l_j^2 - \rho(D_j)^2 - \rho(S_j)^2|}{2.\rho(D_j).\rho(S_j)}\right); \qquad (0 \le Arc\cos(\theta) \le \pi) \qquad (4.8)$$

Then, the hook horizontal travel time: $T_v = \max(T_a, T_w) + \alpha.\min(T_a, T_w)$ (4.9)

And the hook vertical travel time: $T_h = |ZS_i - ZD_i| / V_h$ (4.10)

The hook travel time (or hoisting time) $T(S_j,D_j)$ can be expressed as

$$T(S_j,D_j) = \max(T_h, T_v) + \beta.\min(T_h, T_v) \qquad (4.11)$$

Where: V_a is the radial velocity of trolley (m/min);

V_ω is the slewing velocity of jib (r/min);

V_h is the hoist velocity of hook (m/min).

α and β are two parameters between 0 and 1; The coefficient α represents the degree of coordination of hook movement in radial and tangential directions in the horizontal plane. According to Kogan (1976), the horizontal simultaneous movement of crane operations in lifting objects for experienced crane operators is assumed to be 76% of the total duration of the cycle. Hence, α is assumed to be 0.25. The coefficient β represents the degree of coordination of hook movement in vertical plane. The vertical simultaneous movement of crane operations is assumed to be small for high-rise building construction where the lifting assignment needs to be lifted to a level that is clear of the building before radial movements can be activated. Therefore, β is assumed to be 1, i.e. the hook move consecutively in two planes (Zhang et al., 1999).

Similarly, the hook travelling time from the last demand point to the supply point of the n^{th} lifted assignment (without load) $T(D_{j-1},S_j)$ is computed by the same model. The delay time for loading at S_j and the delay time for unloading at D_j : $T_L(S_j)$ and $T_U(D_j)$ respectively, depend on the skills of workmen, the type of lifted elements and the type of the lifted gear. $T_L(S_j)$ and $T_U(D_j)$ can be obtained by observations on site or based on experiences.

The hoisting time model above is for a single lift, the model to compute the hoisting time of each crane for a group of lifted modules and according to batches is shown in the next subsection.

4.2.2.2 Calculate the Hoisting Time of a Group of Tasks According to Batches

The hoisting time for each crane can be counted as the total time that the crane hoists all the lifted jobs assigned to it. However, to ensure the logical installation order, it assumes that the installation of precast components is performed according to batches (section 3.1.4.1 and 3.5). This assumption may eventually result in longer hoisting time for each crane, since the crane may have to wait until all precast components in the previous batch are installed before it can install its assigned jobs in the new batch. For example, the installation of the beam should be postponed until the two columns below it are installed and gain enough strength to resist the load from the beam. The total hoisting time (the total rental time to be precise) of each crane is defined as the total time from the first lifted module to be installed to the completion of installing the last lifted module delivered by that crane.

The hoisting time is calculated in batch manner according these below formulas.

$$T^{crane}_{batch\_job} = T^i_k = \sum_{j=1}^{J^i_k} t^i_{k\_j} \qquad (4.12)$$

Or $$T^{crane}_{batch\_job} = T^i_k = \underset{i=1,2,...m}{Max}\left(T^i_k\right) \qquad (4.13)$$

Eq. 4.12 is used if the last lifted job assigned to crane i is in batch k.

Eq. 4.13 is used if the last lifted job assigned to crane i is in batch k'>k.

Where T^i_k is the hoisting time of crane i in batch k.

$t^i_{k\_j}$ is the hoisting time of crane i to lift task j in batch k.

J^i_k is the number of task assigned to crane i in batch k.

Thus, the total hoisting time for each crane is: $T^i_{hoisting} = \sum_{k=1}^{K^i} T^i_k$ (4.14)

The computing of hoisting time for each crane in each batch is demonstrated below.

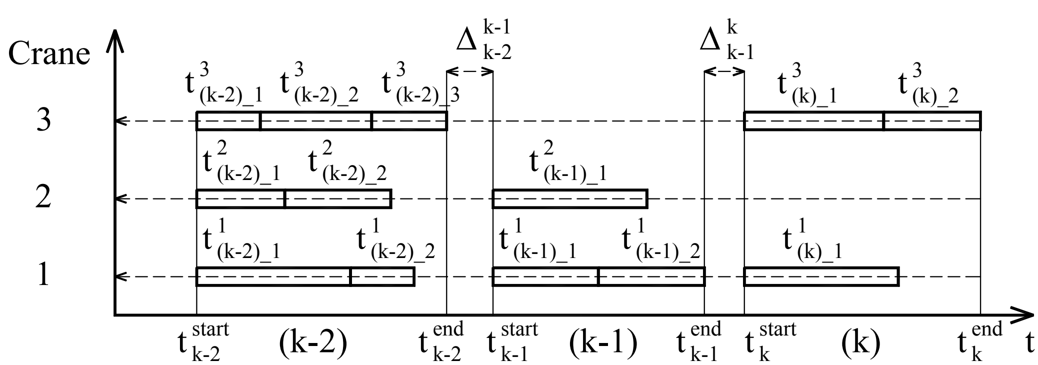


Figure 4.3: Illustration of Calculating the Crane Hoisting Time According to Batches

Where

t_k^{start} : Start time of batch k (Start time of the first task in batch k).

$t_{k\_j}^{i}$: Hoisting time of crane i for task j in batch k.

t_k^{end} : End time of batch k (Finish time of the last task in batch k).

Δ_{k-1}^{k} : Delay time between batch (k-1) and batch k.

4.2.2.3 Final Objective Function

The theoretical value of the hoisting time will not be a perfect representation of the total transportation time incurred by the tower crane(s), as there exists other idle time of the crane(s) due to other constraints and procedures such as technical construction delay or shortage of lifted modules. However, for the purpose of evaluating the performance of different crane positions, the value calculated by the model is adequate enough to suggest the best solution for CLP including the crane(s) model and its locations, the task assignment policies to each supply point and to each crane. The relative economic comparison between different crane positions can also be achieved. The saving in transportation cost may mean not only a reduction in crane hiring period, but in many situations also a shortening of the construction duration (Choi and Harris, 1991).

The objective function for CLP should be:

$$\text{Minimize } T_{total} = \sum_{i=1}^{N_{crane}} T_{hoisting}^{i} \tag{4.15}$$

Or in the form of total rental cost of cranes:

$$\text{Minimize } C_{total} = \sum_{i=1}^{N_{crane}} T_{hoisting}^{i} \times C_{\mathrm{Re}nt}^{i} \tag{4.16}$$

Where $T_{hoisting}^{i}$ is the total hoisting time of crane i, counted from the beginning of the overall installation to the time finishing the last lifted module of that crane.

C_{rent}^{i} is the rental cost of crane i.

4.2.3 Constraints and How to Handle Constraints of CLP

The central problem for applying GA to the constrained optimization problem is how to handle constraints because genetic operators usually yield non-feasible solutions. These invalid solutions, which might be randomly generated by initialising operations or produced by crossover and/or mutation operators during GA iterations, have to be dealt with. There are several techniques to handle constraints with genetic algorithms, namely rejecting strategy, repairing strategy, modifying genetic operator strategy and penalizing strategy (Gen and Cheng, 1996). Each strategy to handle constraints mentioned above has its own pros and cons, depending on the nature of problem-specific search space as well as the type of constraints.

To deal with the constraints of CLP effectively, they are divided into two groups, (1) the conditions of rational chromosomes and (2) the conditions relating to crane operations. Group 1 includes all the conditions that ensure the chromosomes generated by GA are valid while the conditions referred in group 2 further check those solutions to ensure all tasks can be performed. Detailed discussions about these constraints are presented in the next subsections.

4.2.3.1 Constraints Group 1 – Producing a Valid Chromosome

The simple binary bit string representation is prone to present an invalid solution as discussed in section 4.2.1.6. A proper chromosome should satisfy these conditions below.

1. One crane locates only one location:

$$\sum_{k=0}^{Nlocation-1} g_{Nlocation*l+k} = 1 \quad \text{with } \forall\ l = 0 \div (N_{crane} - 1). \tag{4.17}$$

2. One location is entitled to the maximum one crane only - Two or more cranes cannot be at the same location :

$$\sum_{k=0}^{Ncrane-1} g_{l+k*Nlocation} \leq 1 \qquad \text{with } \forall\ l = 1 \div (N_{location} - 1). \qquad (4.18)$$

3. One lifted assignment is located in one supply point only:

$$\sum_{k=0}^{N\sup ply-1} g_{Ncrane(Nlocation+l)+l*N\sup ply+k} = 1 \qquad \text{with } \forall\ l = 0 \div (N_{module} - 1). \qquad (4.19)$$

4. One crane listed in the database is chosen the maximum 1 time – two or more cranes chosen cannot be the same single crane in the database.

$$\sum_{k=0}^{Ncrane-1} g_{Ncrane*Nlocation+Ncrane*Nsmall\_group+N\sup ply*Nsmall\_group+k*Navailable+l} \leq 1 \qquad (4.20)$$

with $\forall\ l = 0 \div (N_{available} - 1)$.

5. One lifted assignment is delivered by one crane only:

$$\sum_{l=1}^{Ncrane} g_{Ncrane(Nlocation+k-1)+kN\sup ply+l-1} = 1 \qquad \text{with } \forall\ k = 1 \div n. \qquad (4.21)$$

For this group of constraints, both rejecting strategy and repairing strategy are not efficient since the number of non-feasible solutions is large. The penalizing approach is also not considered since this is very difficult to evaluate the non-feasible solutions. Hence, modifying genetic operator strategy is employed to treat these constraints. Three specialized genetic operators are designed to create only feasible chromosomes for CLP. (See section 4.2.4)

4.2.3.2 Constraints Group 2 – Operational Constraints

A chromosome that satisfies all the constraints of group 1 may still be rejected if it violates the conditions relating to the lifting operations. These conditions are called operational constraints, which refer to the crane capacity requirements to handle the lifted jobs assigned to it. The operational constraints include the reach requirement and the capacity requirement. To complete a lifted task successfully, one crane must satisfy both two conditions below.

1. It can reach the further point between supply point and installation point.

$$L_{Boom} \geq \max\left(\rho(S_j), \rho(D_j)\right)|_{j=1,..J} \tag{4.22}$$

where j is the total number of lifted jobs assigned to that crane.

2. It has enough capacity to lift the weight at the farthest distance required.

$$\left[Q_{R=\max(\rho(S_j),\rho(D_j))}\right] \geq Q_j \tag{4.23}$$

where $[Q_R]$ is the crane capacity at distance R and Q_j is the weight of lifted module j and the weight of lifting system associated with it.

For this group of constraints, the penalty approach is employed. This approach is chosen with considerations that it is very difficult to establish the penalty function that can effectively guide genetic search toward the promising area of solution space, and that the computations to calculate the fitness function of each chromosome is quite expensive. Therefore, if each newly created chromosome does not satisfy both conditions above, penalty fitness will be given without the normal calculation of fitness process. The penalty fitness is a relatively big constant compare to the expected fitness, equal or larger about 150% of the fitness of the optimal solution to ensure that solution will be eliminated during the GA evolution. (According to the study of Zhang et al., their model can save up to 40% of the hoisting time for horizontal hook movements. In a practical case study (section 5.2.3), the GA model can save up to 60% of the horizontal hoisting time). The crane capacity requirement is more critical than its reach requirement since the tower crane can easily increase its boom length, hence the penalty fitness for the crane capacity should be smaller than the penalty fitness for the reach requirement. For CLP, the penalty fitness for the solution that does not satisfy the reach requirement (eq. 4.22) or the capacity requirement (eq. 4.23) is 10^6 or (10^6-1) minutes respectively. These particular fitness values are also used to identify the case that there is no solution available. The procedure of this technique is illustrated below.

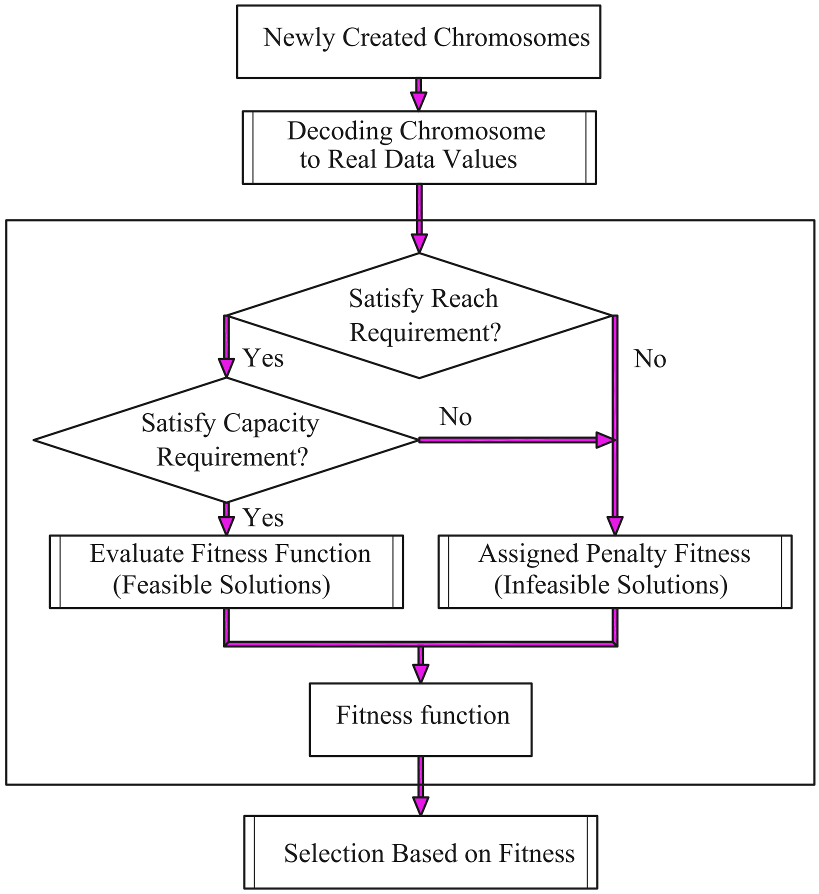


Figure 4.4: Detail Process of Evaluating the Fitness Value with Operational Constraints

4.2.4 Customized GA Operators

This part tries to explain how to construct the specialized operators, and how to judge their effect on the model performance. There are three specialized genetic operators to be built, namely the initialising operator, the mutation operator, and the crossover operator. Each of these operators affects the search process, and (consequently) the chances of finding a successful solution.

4.2.4.1 Combinational Initialiser (Initialising Operator)

The initialising operator's function is to create the initial population of chromosomes randomly. The initialiser should be able to produce valid structure of the solution representation as well as minimize production of non-feasible ones. For CLP, a customized initialiser has been developed to produce only valid chromosome, i.e. the chromosome that satisfies all the constraints in group 1 (eq. 4.17 to 4.21). The value of each group of genes in the chromosome is assigned randomly using a random number generator. The random number generator can generate integer numbers randomly in a range. For example, to assign *two* lifting task to *five* possible cranes, the initialiser runs the random number generator *two times* to generate number randomly *in the range from 1 to 5*. Supposed the generated numbers are 2 and 4, the initialiser can assign value of the two groups of CAG as below.

0	1	0	0	0	0	0	0	1	0	The 2 groups of genes after being initialised.

Figure 4.5: Randomly Generated Value for a Group of Genes in Chromosome

From fig. 4.5 we can see that the first task (group 1) is assigned to the crane 2 (out of 5 possible cranes) while the second task (group 2) is assigned to crane 4. However, for CLG and CDG, there are possibilities of generating invalid chromosomes as illustrated in the figure below.

0	0	1	0	0	0	0	1	0	0	The 2 groups of genes after being initialised.

Figure 4.6: Problem of the Simple Initialiser in CLG and CDG

Suppose the above two groups of genes are CLG for crane 1 and crane 2. It gives the information that the both crane 1 and crane 2 is located at the 3^{rd} location (out of 5 possible ones). This is an invalid solution since it violates the constraint in eq. 4.17. Similar problem is observed with CDG (the constraint in e.q 4.20 is violated).

Moreover, the problem of generating invalid chromosome tends to happen when the number of cranes are large and equal to the number of possible locations or the number of available cranes. It is because the random number generator is hard to always create a "new" number (i.e. different from all the previously generated number) every times, especially to generate the random value for the last crane. For example, to assign four tower cranes to five locations, of which the first three cranes are located at the 1st, 2nd and 4th locations, the random number has only 40% of success to generate the last number (either 3 or 5) to create a valid assignment group of genes. To solve this problem of generating invalid chromosomes, a technique using a temporary array and a so-called "greedy algorithm" is employed. The temporary array has the size of total number of possible solutions. Each gene of the array has an integer value to represent a particular solution. To assign a solution for a group of genes, the random number generator generates one number to select the position of a gene in the temporary array. The integer value of that gene presents the chosen solution. Since the random number generator is checked to generate only the number in the range of the size of the temporary array and the temporary array stores only valid solutions, a generated solution for SPG and CAG always satisfies the constraints in eq. 4.19 and eq. 4.21 respectively. A sample of the initialiser to assign initial solution for SPG or CAG with temporary array is illustrated in fig. 4.7 below.

1 | 2 | 3 | 4 | 5	Create temporary array of N_{supply} or N_{crane} genes with the integer allele set from 1 to N_{supply} or N_{crane}
3 | 4 | 1 | 5 | 2	Swap the genes randomly N_{supply} or N_{crane} times
5 | 3	Use random number generator to select value for N_{small_group} group of genes
0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0	Change from integer to binary presentation

Figure 4.7: Initialiser Applied for Groups of SPG and CAG with a Temporary Array

For CLG and CDG, the greedy algorithm is employed to help create a solution that satisfies those constraints in eq. 4.17, 4.18 and 4.20. Basically, the greedy algorithm eliminates the possibility of generating the same solution more than once for these two types of genes (CLG and CDG) in the complete chromosome. The mechanism of the greedy algorithm is illustrated in fig. 4.8. Each time the initialiser assigns a value for a group of CLG (or CDG), it takes away the same value from the temporary array to ensure that it will not be chosen again. Sample code of the greedy algorithm to assign the initial value for CLG is provided in appendix A.

Possible solution	Chosen solution	Random number range (*)	Random number generated value	Iteration i th
2 | 4 | 5 | 1 | 3	0 | 0 | 0	(0-4)		0
2 | 5 | 1 | 3	**4**	(0-4)	**1**	1
5 | 1 | 3	**4** | **2**	(0-3)	**0**	2
5 | 1	**4** | **2** | **3**	(0-2)	**2**	3

Figure 4.8: Mechanism of the Greedy Algorithm

(*) the first position of the temporary array start at 0 in C++ computer language.

A sample of the initialiser to assign initial solutions for CLG or CDG with a temporary array is illustrated in fig. 4.9 below.

1 | 2 | 3 | 4 | 5	Create temporary array of $N_{location}$ or $N_{available}$ genes with the integer allele set from 1 to $N_{location}$ or $N_{available}$
2 | 4 | 5 | 1 | 3	Swap the genes randomly $N_{location}$ or $N_{available}$ times
4 | 2	Use "greedy algorithm" to select the N_{crane} genes
0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0	Change from integer to binary presentation

Figure 4.9: Initialiser Applied for Groups of CLG and CDG with a Temporary Array

The specialized initialiser is a combination of a simple initialiser for CAG and SPG and an initialiser with temporary array and the greedy algorithm for CLG and

CDG. Thus, the initialiser for CLP is called Combinational Initialiser. The pseudo code of the initialiser for CLP is presented in appendix A.

4.2.4.2 Combinational Permutation (Combinational Swap Mutation)

The mutation operation applied in this problem is permutation to ensure that the genetic materials related to different groups of genes are not mixed. The specialized mutation is designed in the way that it not only ensures to produce feasible solutions, but also more importantly, is capable of introducing new genetic material (that may not present in the current population). Successful mutation is the one that can help GA to "jump" out of local optimum and explore all over the search space.

To apply mutation (permutation) operation; there is a need to define which part of genes the mutation will take place. The permutation will be performed in any of $2*(N_{crane} + N_{small\_group})$ groups of genes. The number of permutation in one chromosome is defined by the mutation rate. There may be more than 1 group of genes being mutated, or only one group of genes is changed or mutation does not take place. When the mutation happens, it will create a *new* chromosome (i.e. different from the parent). The illustration of a mutation operation in a group of genes is as follow:

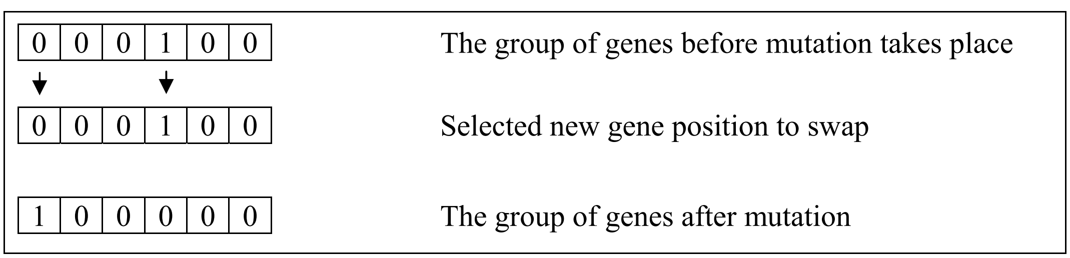


Figure 4.10: Permutation Takes Place in a Group of Genes

Suppose the above group of genes is the CLG; Fig. 4.10 shows that before mutation, the crane is located at the 4th location while after mutation, the crane is positioned at the first location. Any arrangement of the genes has the same possibility to be changed and it is chosen randomly. This mutation is applied for SPG and CAG.

However, this simple mutation has problems in CLG and CDG where the constraints in group 1 impose the conditions that one location is assigned to one crane only and one crane in the database is chosen a maximum of 1 time (the same as in TSP). The problem is illustrated in fig. 4.11 below.

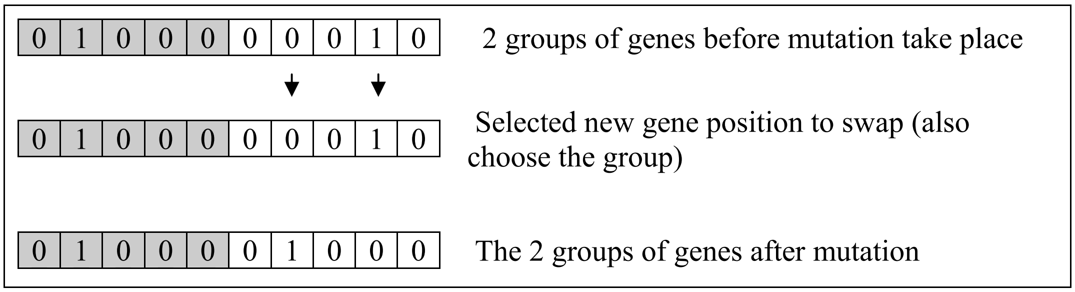


Figure 4.11: Problem of the Simple Mutation in CLG and CDG

Suppose the above two groups of genes are CLG; we can see that after simple mutation takes place in the second group of genes. Now the two groups show the information that the crane 1 and 2 is in the same location (the 2nd one out of 5). This violates the condition in eq. 4.18. Thus, the permutation for the CLG and the CDG is applied between two groups of genes. The mechanism of this mutation is that it simply swaps the contents of the two groups of genes as illustrated in fig. 4.12 below.

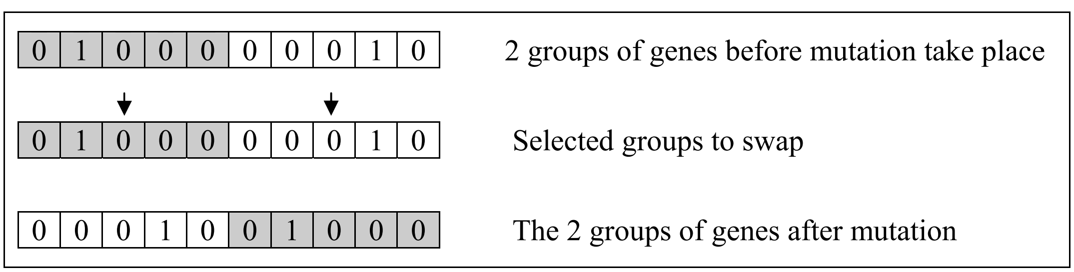


Figure 4.12: Permutation Applied for Groups of CLG and CDG

From fig. 4.9 above, we can see that the problem of violating constraints has not happened. However, now the mutate operation is able to swap the existing genetic materials in the group of genes without being able to introduce the new genetic material to the chromosome. For example, the current information stored in the chromosome is crane 1 and crane 2 located at 2nd and 4th locations, respectively. The mutation can swap the locations (2nd and 4th) for the two cranes; however, it cannot change from these locations to the ones that are not chosen (i.e. the 1st, 3rd and 5th locations). To overcome this drawback, a temporary array that contains all possible solutions is created and permutation is performed in this temporary array. The permutation applied for groups of CLG and CDG with the temporary array is illustrated as in fig. 4.13.

0 1 0 0 0 0 0 0 1 0	2 groups of genes before mutation take place
2 4	Change from binary to integer presentation
1 2 3 4 5	Create temporary array of 5 possible locations/cranes
2 4 3 1 5	Swap the chosen genes to the 1st and 2nd positions
2 4 3 1 5	Randomly choose a pair of gene positions to swap
2 5 3 1 4	The array after being swapped
0 1 0 0 0 0 0 0 0 1	Change from integer to binary presentation

Figure 4.13: Permutation Applied for Groups of CLG and CDG with Temporary Array

As can be seen in fig. 4.13, the permutation with temporary array can introduce new genetic material to the chromosome (location/crane 5th is chosen).

In short, the mutation in CLP is the permutation that acts differently in different part of the chromosome, as a simple permutation in a group of genes or as a permutation between two groups of genes with temporary array. This mutation is called combinational permutation (or combinational swap mutation).

The pseudo code for the combinational permutation is included in app. A.2

4.2.4.3 Combinational Crossover: 1-Point Crossover and OPMX

Crossover operator is the main and most important GA operator. Crossover creates new offspring by combining parts of the parents' genes. The parents are chosen based on their fitness; and the crossover is expected to produce "better" chromosomes in each generation. A good crossover operator is not only able to search the local region for the optimum solution but also able to scan all over the search space. For the famous TSP, the travelling sale man has to go all the cities once, the crossover applied is PMX crossover (See Gen and Cheng, 1996) which basically swaps the gene's positions within the chromosome. But for the CLP, when number of cranes used is smaller than the number of possible locations and/or the number of cranes in library, the special customized Open Partial Mapped Crossover (OPMX) not only swaps the lotus within the chromosomes, but also exchanges different lotus of other chromosome. This feature ensures that a new chromosome is created based on chosen parent's chromosomes. The working mechanism of OPMX is illustrated in fig. 4.14 with the integer presentation.

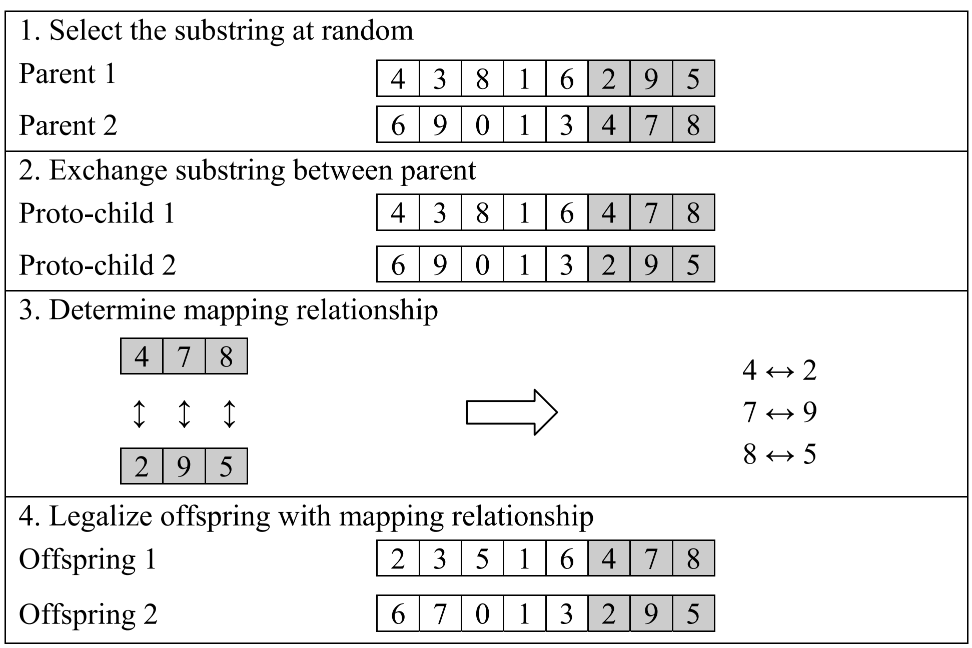


Figure 4.14: OPMX for CLG and CDG of CLP Chromosome

In the original PMX (see Gen and Cheng, 1996), since every chromosome has the same set of alleles, this crossover is only to maintain the absolute position of a gene allele in the offspring. For the CLP, when the number of cranes to be used is smaller than the number of possible locations or the number of available cranes, different chromosomes may contain different set of alleles (e.g. 1, 2, 3, 4, 5, 6, 8, and 9 in parent 1 and 0, 1, 3, 4, 6, 7, 8, and 9 as in parent 2). One chromosome may contain the genetic material that is not available in other chromosomes (e.g. allele 2 and 5 in parent 1 is not available in parent 2 while the allele 0 and 7 in parent 2 are not available in parent 1). It can be seen from fig. 4.14 that the OPMX not only preserves the absolute position of a gene allele within the chromosome (as in the original PMX) but also exchanges the genetic material between parent chromosomes. For example, offspring 1 has both allele 7 from parent 2 and allele 5 from parent 1 and its allele set differs from both parents. This is the new feature of OPMX.

The OPMX is applied to CLG and CDG, while the simple 1-point crossover (1PX) is applied to SPG and CAG. This specialized crossover operator has been designed to maintain the integrity of the chromosome. It is able to generate reordered lists without duplicating any element in the list (permutation coding), exchange genetic materials from parents, as well as perform simple exchange crossover in other parts of the chromosome. The specialized crossover for CLP is called the combinational crossover.

The pseudo code for the combinational crossover is included in app. A.3.

4.2.5 Outline of the GA Process for CLP

The flow chart for GA model is as below:

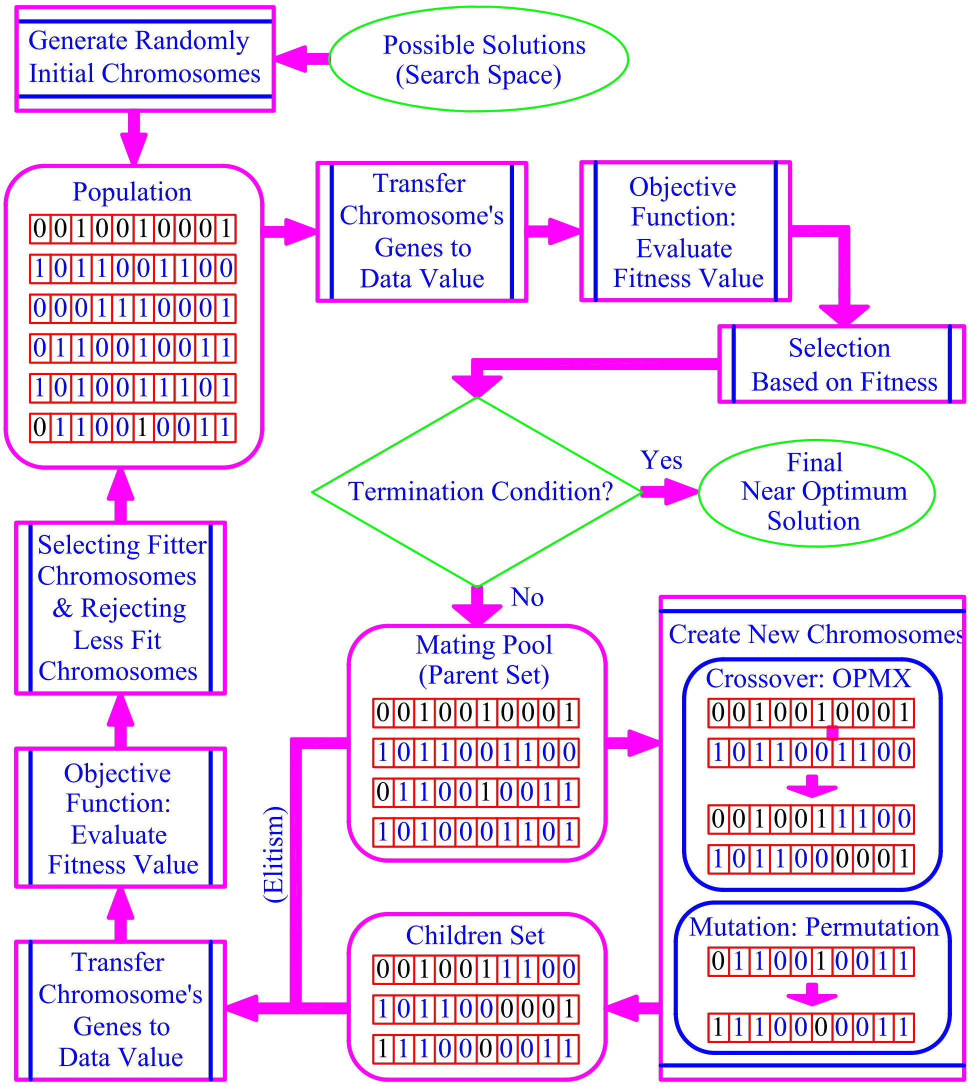


Figure 4.15: Flowchart of the GA Model of CLP

4.2.6 Optimize the GA Parameters for CLP

One of the difficult decisions to make is to choose a set of values for various GA parameters. The focus has been centred on the population size, the crossover rate and the mutation rate. To perform the optimization tests to choose the set of values for these GA parameters, one may consider the effects of varying parameters to the GA on-line and off-line performance or use another GA to optimize the parameters of the considered GA, or spend time testing different GA parameters by computer (Mitchell, 1997). On-line performance is the average of all fitnesses of all individuals up to and including the current generation, while off-line performance is the average of the best fitness seen up to each evaluation step. On-line and offline performances are introduced to asssess the efficiency of GA by Goldberg (1989a) and Haupt et al. (1998).

Good parameters for CLP are found by experiments: conducting tests with different population size with different scale problems, different rate of GA operators (crossover and mutation), and monitoring the GA performance.

These tests start with recommended parameters from previous research of GA experts. These recommended parameters are summarized below.

Table 4.1: Recommended GA Parameters

Researchers	Population Size	Crossover Rate	Mutation Rate	Note
De Jong (1975)	50-100	~ 0.6 per pair of parents	0.001 per bit	
Grefenstette (1986)	30	0.95	0.01	Using elitism
Schaffer et al (1989)	20-30	0.75 - 0.95	0.005 - 0.01	

4.2.6.1 Population Size: Test – Discussion – Recommendations for CLP

The unique character of GA technique as compared to other search method is that it works with a set of solutions (a population) rather than with a single solution. How to decide the number of chromosomes or the GA population size is not an easy task. If the population size is too small, the GA is prone to converge very fast and to be "trapped" in "local optimum" and thus GA has not found the "best solution" yet. On the other hand, if a population size is large, GA may have more capability to evolve and "escape" from "local optimum" as well as to find "better solution". However, large population size will take longer time for the program to converge. It may be surprising that very big population size usually does not improve performance of GA (in the sense of speed of finding solution). The objective of the population test is to find a suitable number of chromosomes in the population to set as default value for CLP.

It is noticed that the scale of CLP can be varied, which can result in significantly different size of the encoded chromosomes. Therefore, using a fix number of population size (such as 30) does not seem to be suitable. One approach that assigns the size of population proportionally to the size of integer-encoded chromosome is proposed. It should be also noted that the representation scheme chosen for CLP is binary bit string while GA operator works with permutation scheme (section 4.2.1.5). Hence, the size of encoded chromosome with integer representation is calculated according to eq. 4.2. Three independent tests with population size of $0.5*L_{integer}$, $1*L_{integer}$ and $2*L_{integer}$ are implemented.

Tests for the population size are conducted with small examples of the crane capacity test series (section 5.1.1). The selected test results of scenarios 1 and 4 are presented below. In the examples, there are only 4 main structures to install, namely the two columns at D_1 and D_2, a structural precast wall at D_3 and a core lift at the centre of the building D_4. There are 3 possible locations for the tower crane to operate and there also has two possible supply points for the only tower crane used. The search space is $3*4^2*4*1$ = 192 possible solutions.

GA test is conducted with P_x =0.9, P_{mut} = 0.5, $P_{replace}$ = 0.25, and $N^{total}_{generations}$ =50. The size of the integer-encoded chromosome is 2*(1+4) = 10, thus the population size is tested with 5, 10 and 20.

The layout of the example is illustrated in fig. 4.16.

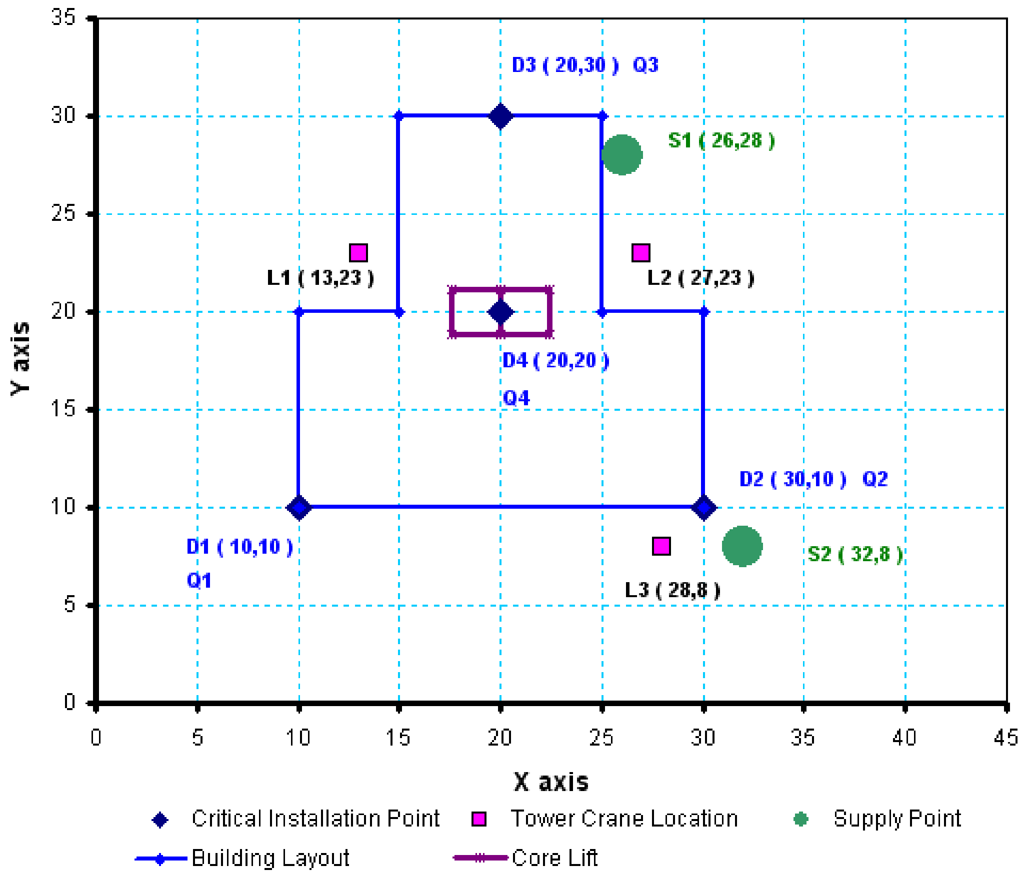


Figure 4.16: Tower Crane Layout – Crane Capacity Test Scenarios

<u>*Scenario 1:*</u> The weight of the four elements are $Q_1 = Q_2 = 4$ ton, $Q_3 = 6$ ton, and $Q_4 = 8$ ton, accordingly. The results are:

The location L_1 governs with the total hoisting time of 3.00 minutes.

The GA performance with different population size is illustrated in figures 4.17, 4.18, and 4.19.

<u>*Scenario 4:*</u> The weight of the four elements are $Q_1 = 4$ ton, $Q_2 = 10.8$ ton, $Q_3 = 6$ ton, and $Q_4 = 10$ ton, accordingly. The results are:

The location L_3 governs with the total hoisting time of 3.39 minutes.

The GA performance with different population size is illustrated in figures 4.20, 4.21 and 4.22.

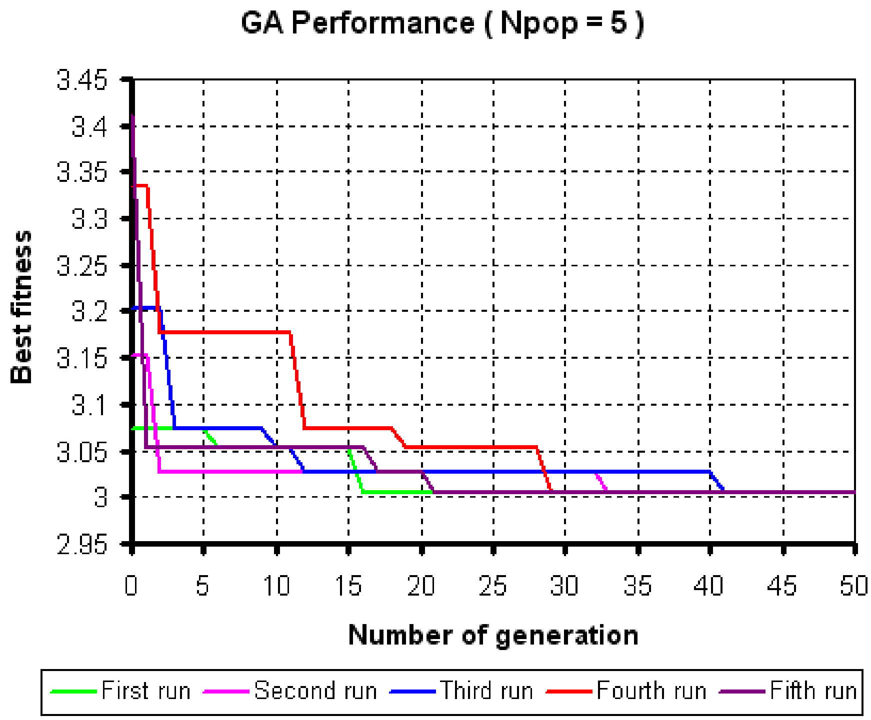


Figure 4.17: GA Performance in 5 Independent Runs of Crane Capacity Tests Scenario 1, N_{pop} = 5

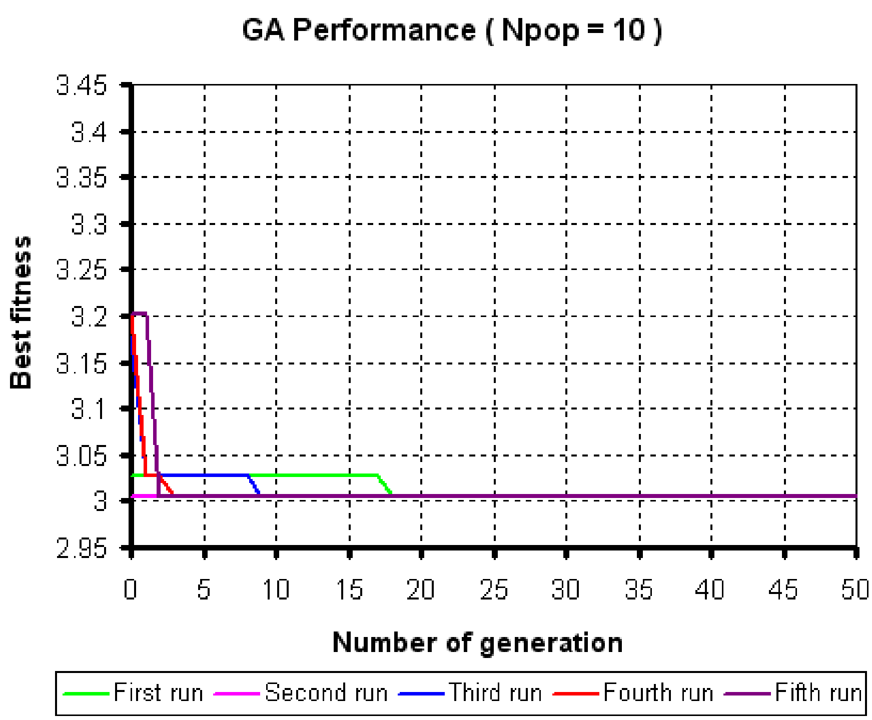


Figure 4.18: GA Performance in 5 Independent Runs of Crane Capacity Tests Scenario 1, N_{pop} = 10

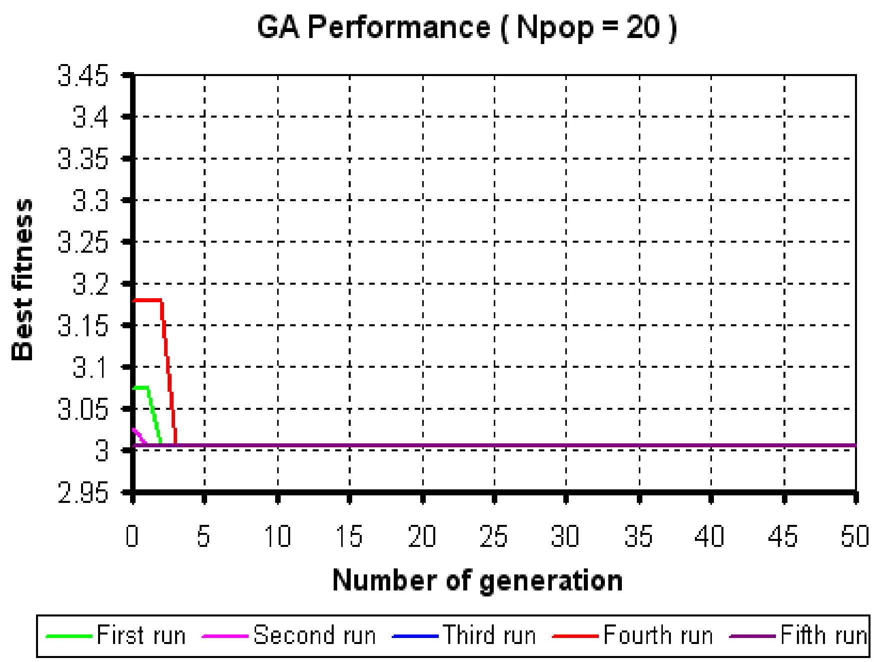


Figure 4.19: GA Performance in 5 Independent Runs of Crane Capacity Tests Scenario 1, N_{pop} = 20

Another test conducted is scenario 4 of crane capacity tests (section 5.1.1).

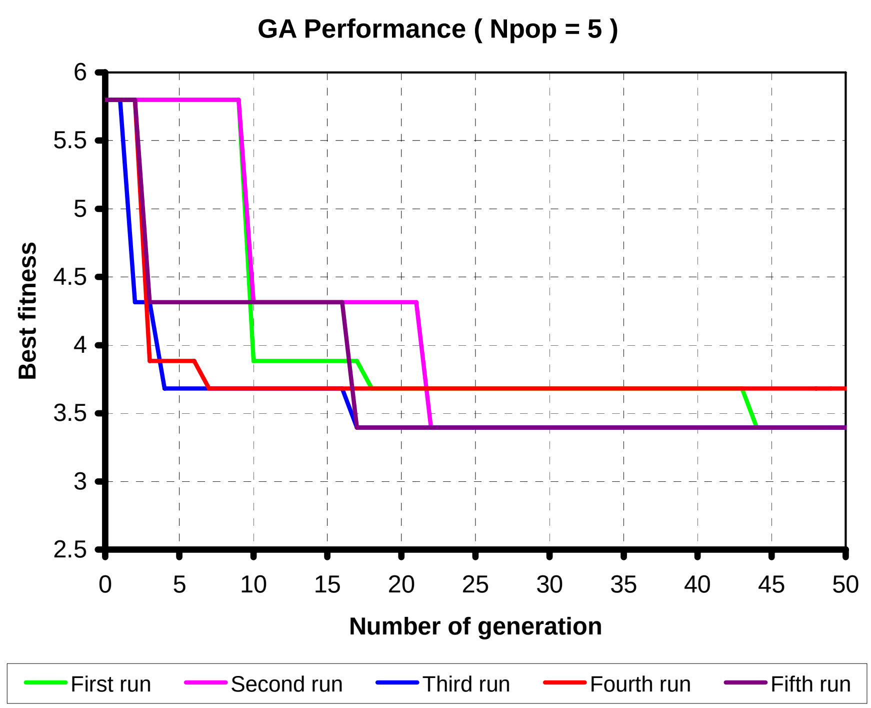


Figure 4.20: GA Performance in 5 Independent Runs of Crane Capacity Tests Scenario 4, N_{pop} = 5

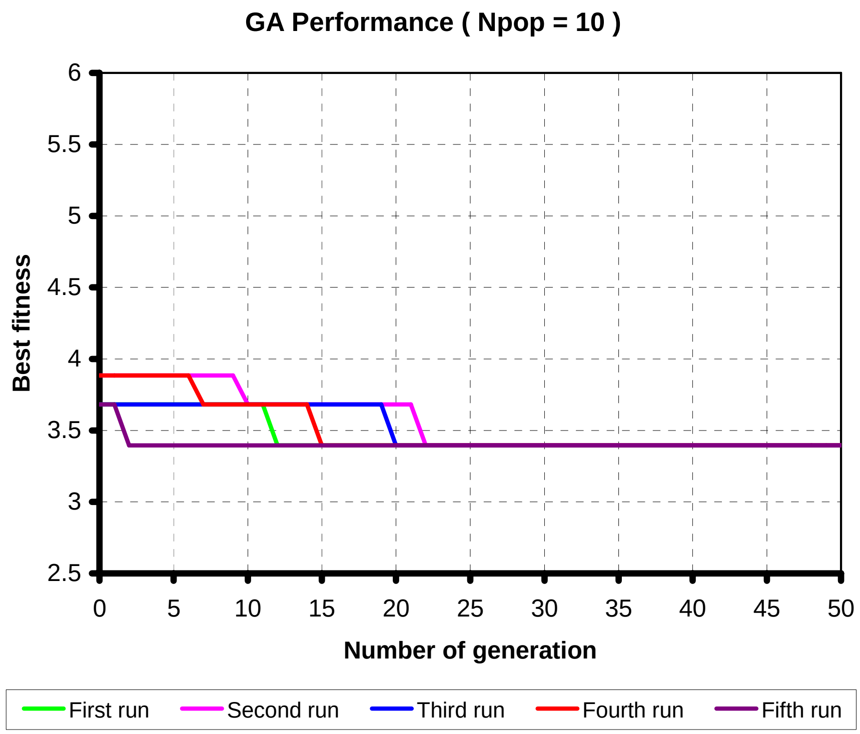


Figure 4.21: GA Performance in 5 Independent Runs of Crane Capacity Tests Scenario 4, N_{pop} = 10

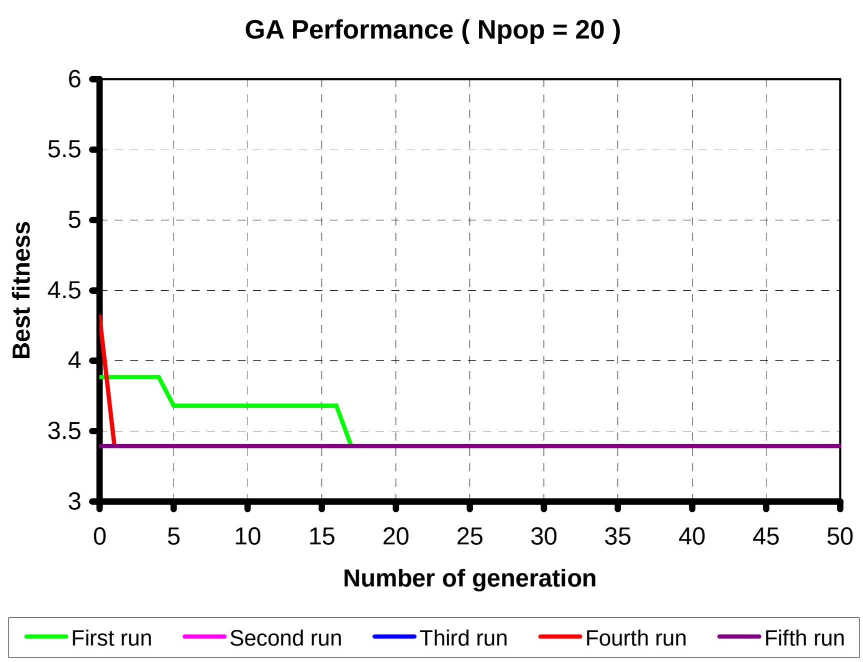


Figure 4.22: GA Performance in 5 Independent Runs of Crane Capacity Tests Scenario 4, N_{pop} = 20

For the particular examples considered, in the first test, for the case with N_{pop} = 5, it needs about 15 to 40 generations to find the best solution while for the case with N_{pop} = 10, only 2 to 20 generations are needed. For the case of N_{pop} = 20, the optimum is found with less than 5 generations. A bigger population may help to maintain the diversity of the population, and thus increase the chance of finding the optimum solution. However, a big population is not suitable for large-scale problems with complicated objective function since it may result in a long time for convergence. A reasonable population size may find the optimal solution faster (i.e. GA may find the best solution after a number of generations in shorter time). From this point of view, it is recommended to use the population size of $L_{integer}$. It is also noted that, the population size of 2*$L_{integer}$ is too big for the current test since the best solution can be found from the random solutions in the initial population.

4.2.6.2 Mutation Rate: Test – Discussion – Recommendations for CLP

Mutation operator takes place with its determined rate. A small mutation rate may limit GA operation to search all over the search space, thus constrain it in a local region while a high rate of mutation operations tend to lead GA to random search process. The customized mutation operation for CLP is designed in such a way that it always randomly create 'new' chromosome by swapping or by introducing new value for one or few lotus of the parent. Both processes are applicable to CLG and CDG while for SPG and CAG, only the swapping operation is introduced since there is no special restriction for this type of genes.

The experiment data is as in the symmetric test – scenario 5 (section 5.1.2). In the example, there are 2 possible crane locations, 4 lifted modules and 3 supply points. Both crane locations and demand points have a vertical line of symmetry. The tests are conducted with $P_x = 0.9$, $P_{replace} = 0.25$, $N^{total}_{generations} = 100$ and $N_{pop} = 10$. The first test is conducted with $P_{mut} = 0.5$ and $P_{mut} = 0.1$. GA performances in the first test are below.

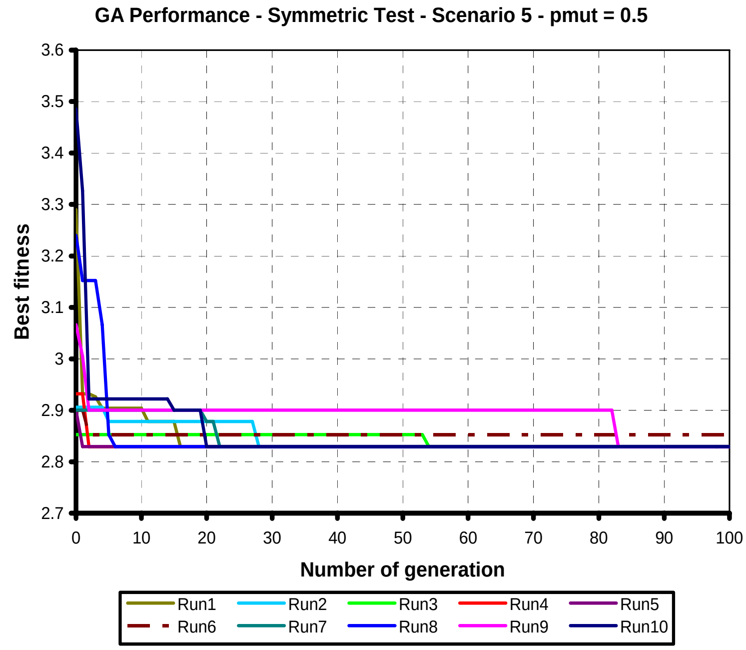


Figure 4.23: GA Performance in 10 Independent Runs of Symmetric Test 1 Scenario 5, $P_{mut} = 0.5$

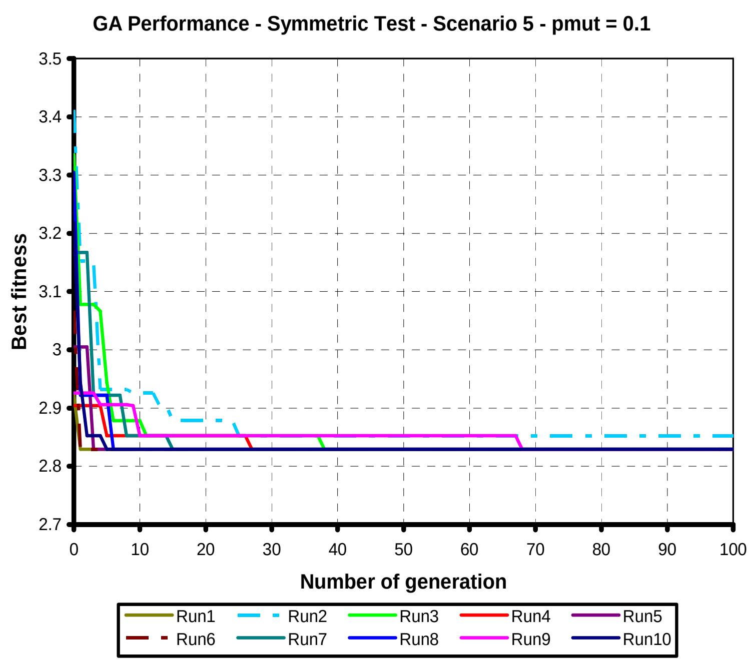


Figure 4.24: GA Performance in 10 Independent Runs of Symmetric Test 1 Scenario 5, $P_{mut} = 0.1$

From the above figures, it can be seen that GA performance with p_{mut} = 0.1 seems to be better with faster convergence. In the case of worst performance within 10 times, it also shows how GA manages to get "better" results rather than randomly evolve as with p_{mut} = 0.5.

The experimental data of the second test is as in the symmetric test – scenario 3 (section 5.1.2). In the example, there are two possible crane locations, 4 lifted modules and 4 supply points. The building outline, crane locations, supply point and demand points have the same vertical line of symmetry.

Again, the GA performance with p_{mut} = 0.1 is proven to be better than that in the case with p_{mut} =0.5. As shown in figures 4.21 and 4.22, the GA performance with p_{mut} = 0.1 is more consistent with concentrated patterns. Besides, the role of mutation operation is also illustrated in run 4 in fig. 4.22 since the GA can "jump" from the local optimum (after more than 80 generations).

Additional experiments have been done with small mutation rate of 0.01 as recommended in table 4.1. However, the GA performance is worse than the case of mutation rate of 0.1. With such small mutation rate, GA rapidly converged and was trapped in local optimum (see fig. 4.23 to 4.28). The experimental data of the third test is as in the number of crane test (section 5.1.7). In the example, there are 3 possible crane locations, 4 lifted modules and 2 supply points. Both crane locations and demand points have a vertical line of symmetry. The installation order of the four jobs is presented in the priority matrix: 3-3-2-1. The third series of tests are conducted with the number of crane as 1, 2, and 3. GA parameters are set with crossover rate of 0.9, replacement rate 0.25, number of generations 100 and 2 mutation rates of 0.01 and 0.1.

GA performances in the second test with different mutation rates of 0.5 and 0.1 are given in fig. 4.21 and 4.22.

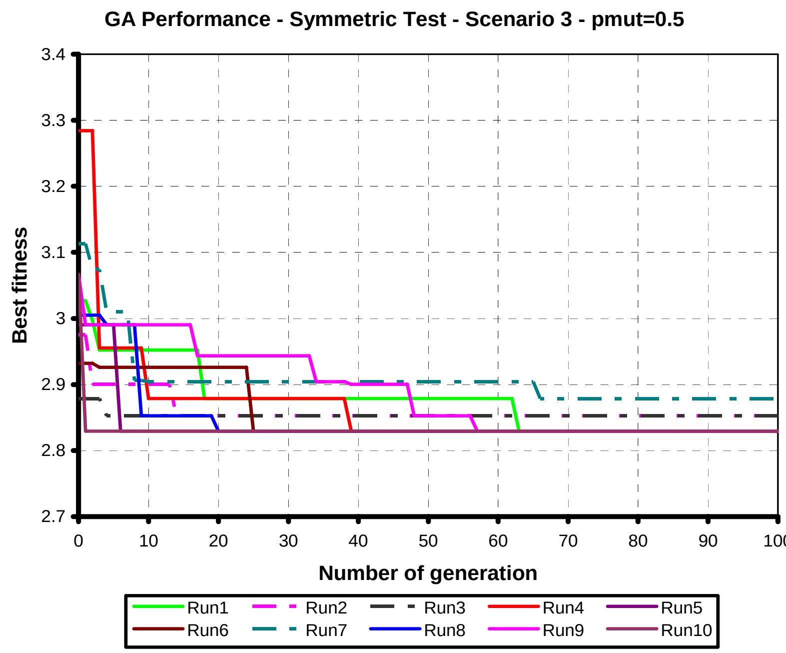


Figure 4.25: GA Performance in 10 Independent Runs of Symmetric Test 2 Scenario 3, P_{mut} = 0.5

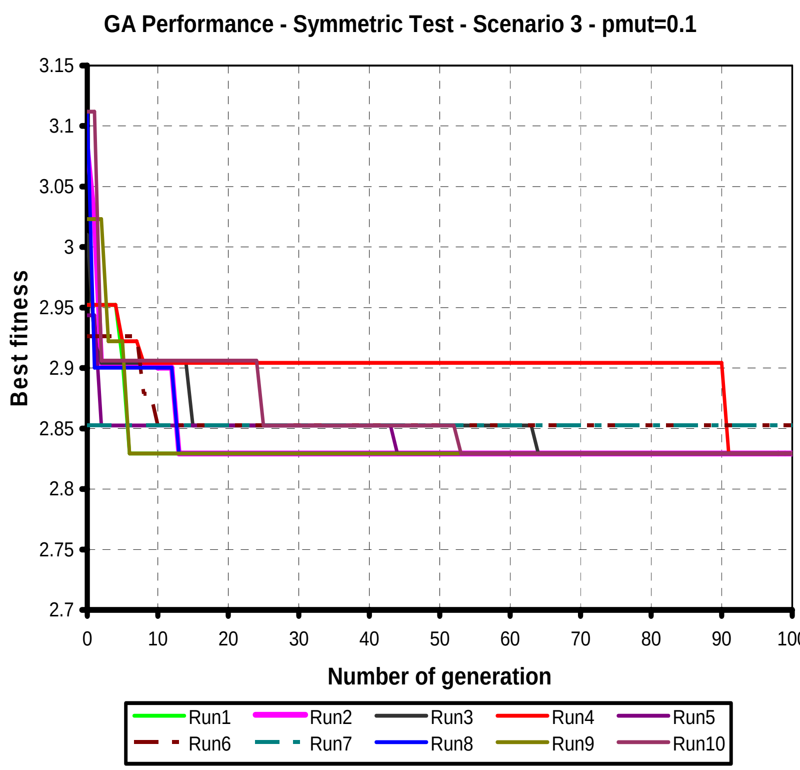


Figure 4.26: GA Performance in 10 Independent Runs of Symmetric Test 2 Scenario 3, P_{mut} = 0.1

GA performance in the third tests with mutation rates of 0.1 and 0.01 are summarised below.

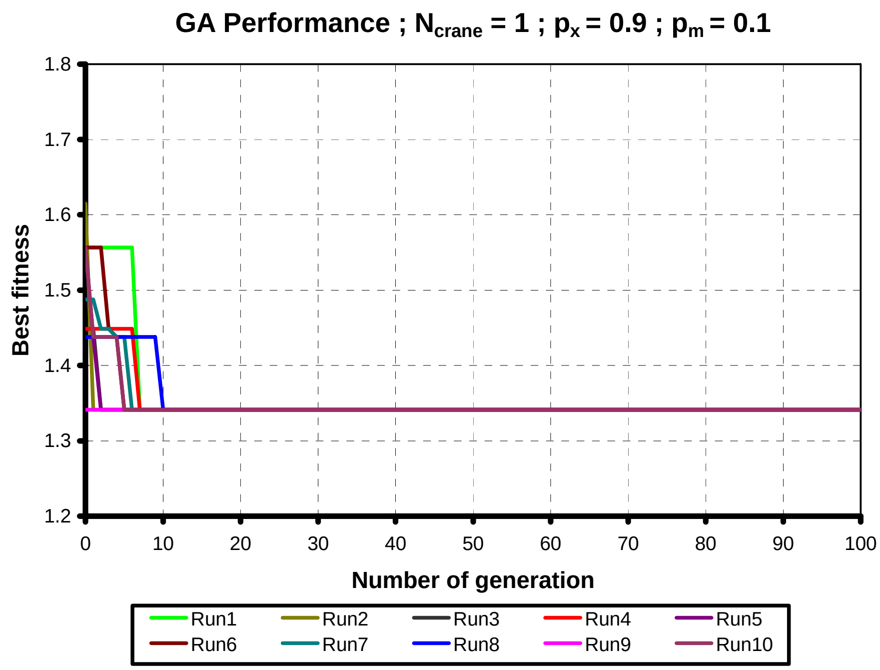


Figure 4.27: GA Performance in 10 Independent Runs of Number of Crane Test 3 Scenario 1 (N_{crane} = 1), P_{mut} = 0.1

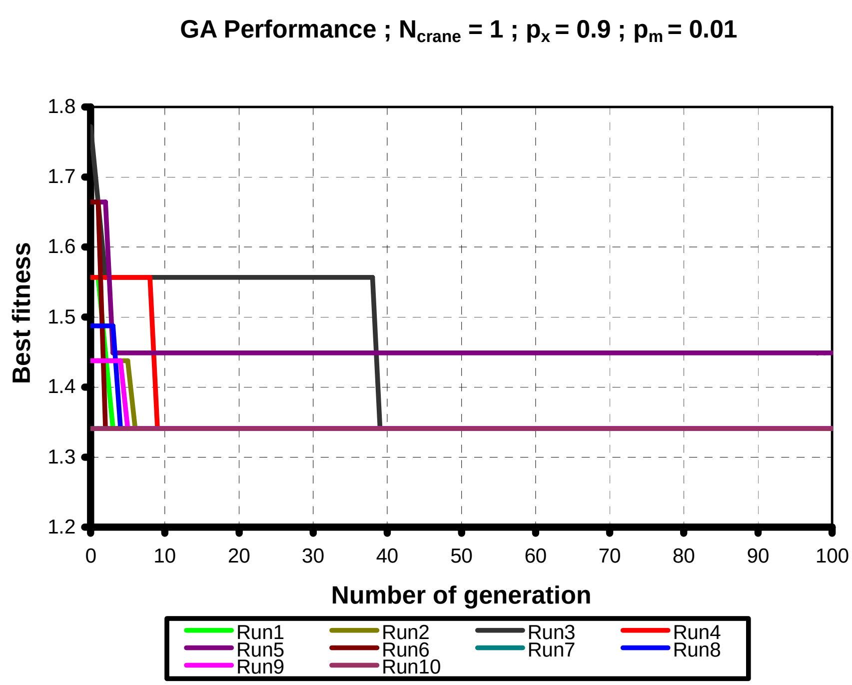


Figure 4.28: GA Performance in 10 Independent Runs of Number of Crane Test 3 Scenario 1 (N_{crane} = 1), P_{mut} = 0.01

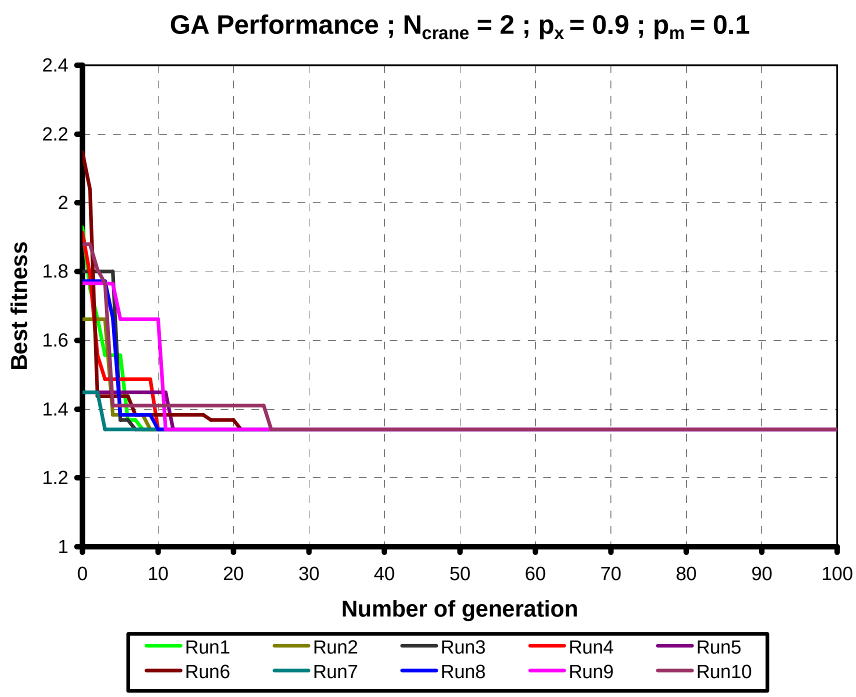


Figure 4.29: GA Performance in 10 Independent Runs of Number of Crane Test 3 Scenario 2 (N_{crane} = 2), P_{mut} = 0.1

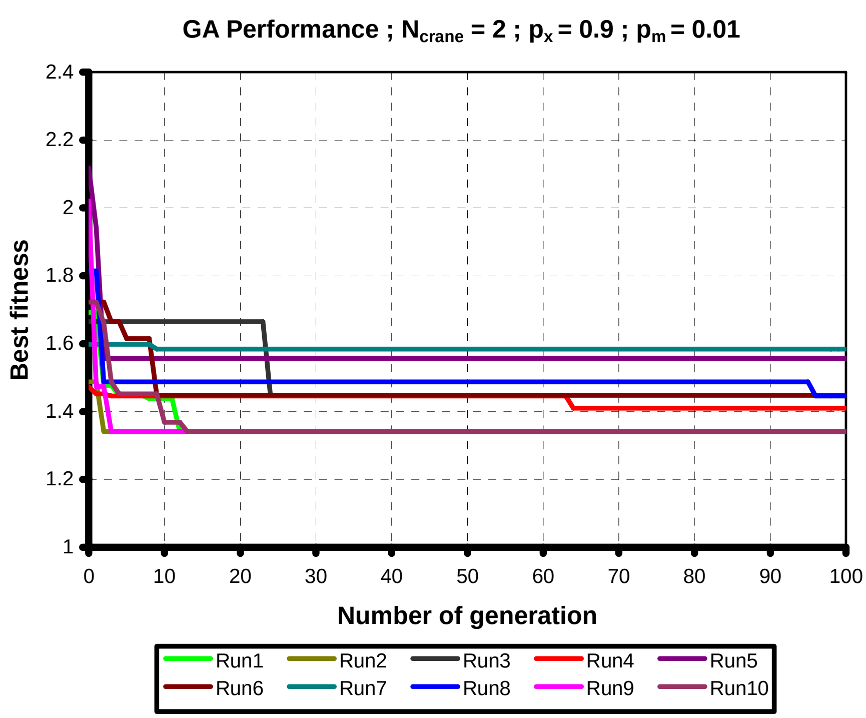


Figure 4.30: GA Performance in 10 Independent Runs of Number of Crane Test 3 Scenario 2 (N_{crane} = 2), P_{mut} = 0.01

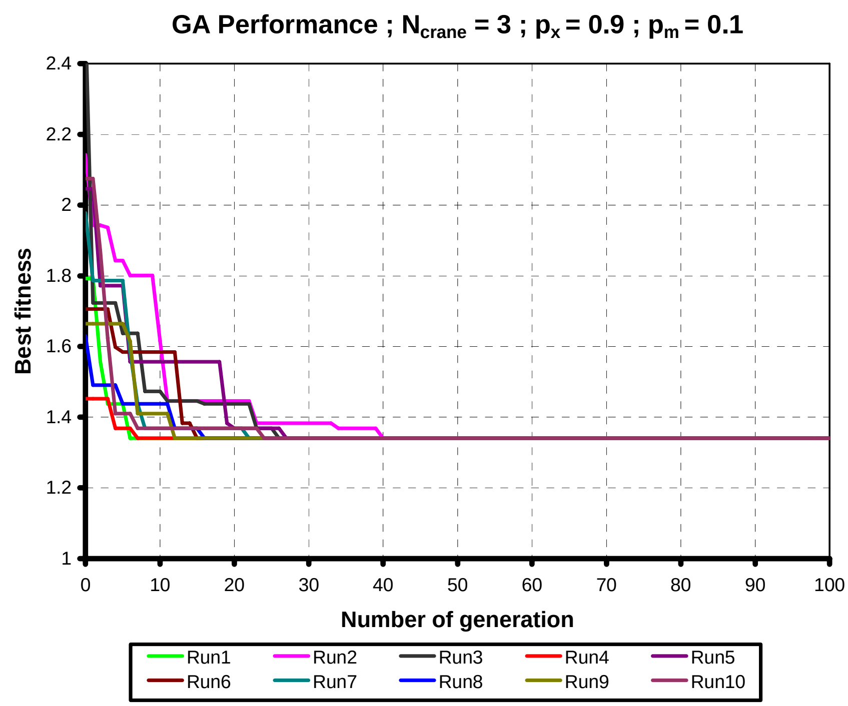


Figure 4.31: GA Performance in 10 Independent Runs of Number of Crane Test 3 Scenario 3 ($N_{crane} = 3$), $P_{mut} = 0.1$

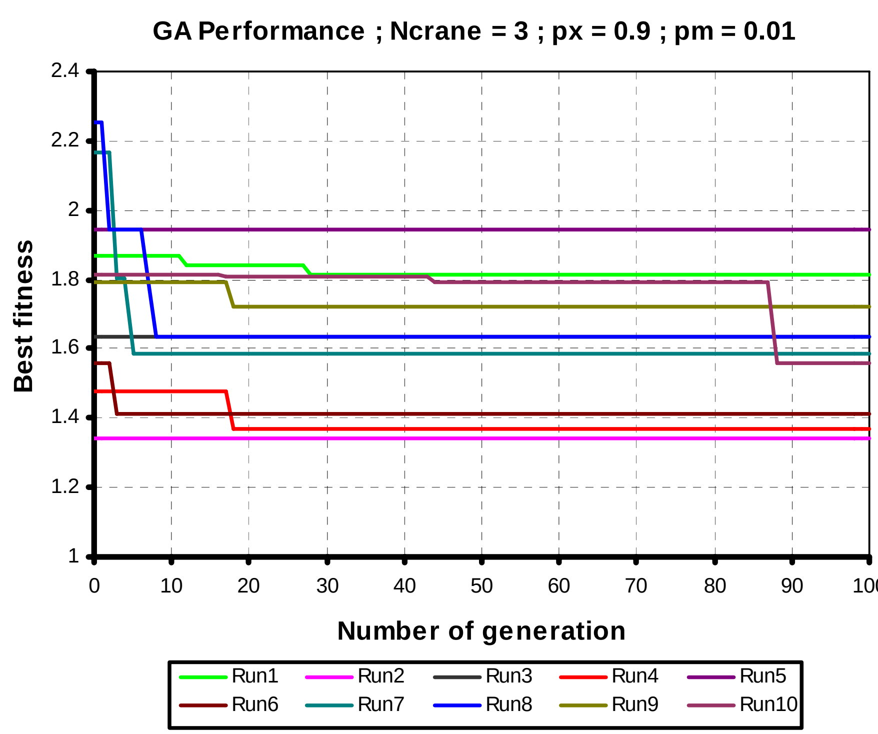


Figure 4.32: GA Performance in 10 Independent Runs of Number of Crane Test 3 Scenario 3 ($N_{crane} = 3$), $P_{mut} = 0.01$

4.2.6.3 Crossover Rate: Test – Discussion – Recommendations for CLP

To choose a suitable crossover rate for CLP, two series of tests are conducted with different crossover rates and the GA performances of each series of tests are monitored. Each series of 3 scenarios with the number of crane are 1, 2 and 3. For each scenario, there are two tests with 2 different crossover rate of 0.6 and 0.9. Both tests are conducted with experimental data as in the number of crane test, as mentioned above in the third test of mutation tests.

Other GA parameters are set with P_{mut} = 0.5, $P_{replace}$ = 0.25 and $N_{generations}^{total}$ = 100. $N_{pop} = 2*(N_{crane} + N_{small\_group})$ in both scenarios. There are also three scenarios of number of crane used, (1, 2 and 3) so the population size are 10, 12 and 14 respectively. The difference between the two tests is the installation order of lifted modules. In the first series of tests, priority matrix is: 1-1-1-1 (i.e. all 4 lifted module have the same priority in the lifting sequence). In the second series of tests, priority matrix is: 3-3-2-1 (i.e. the installation sequence is with 3 batch requests, the last lifted module has to be installed first, then the third one and the first two elements).

GA performances of each series of test are illustrated in fig. 4.29 to 4.40. From these figures, it can be seen that GA performances with P_x = 0.9 and P_x = 0.6 are not so different with the results of P_x = 0.9 slightly better in most of the cases. These results show that, for these small examples, the crossover rate of 0.6 is good enough. It is because, with the current P_x = 0.6, the new chromosomes created in each generation are from 30 to 60% of the populations with the $P_{replace}$ = 0.25. The corresponding new offspring each generation with P_x = 0.9 is in the range of 45 to 90% of the population size. The P_x = 0.9 is chosen for CLP since it may have better behaviour in large scale test.

GA performance of the first series of tests – No batch request.

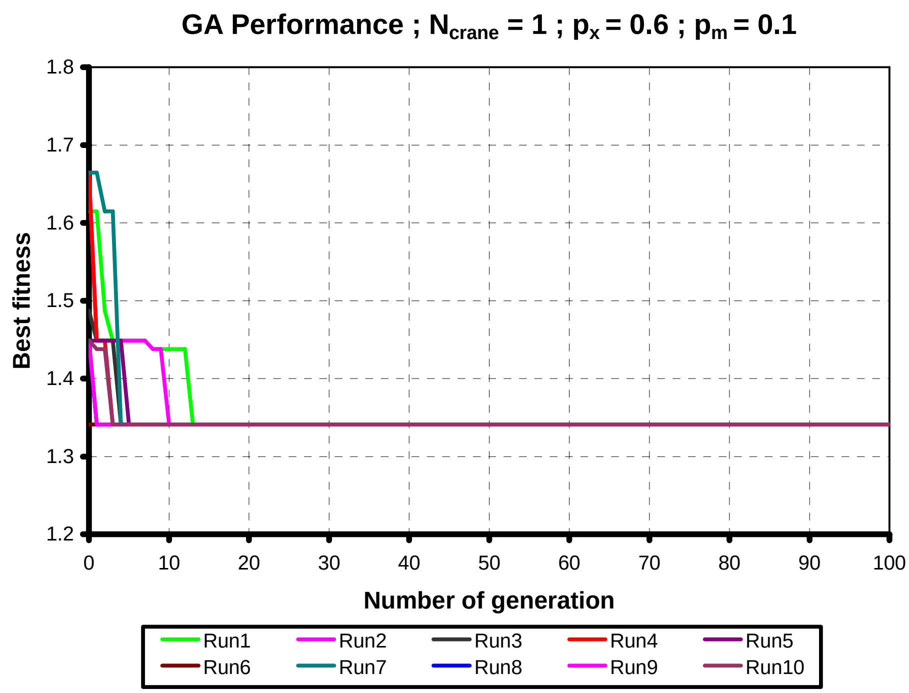


Figure 4.33: GA Performance in 10 Independent Runs of Number of Crane Test 1 Scenario 1 (N_{crane} = 1), P_x = 0.6

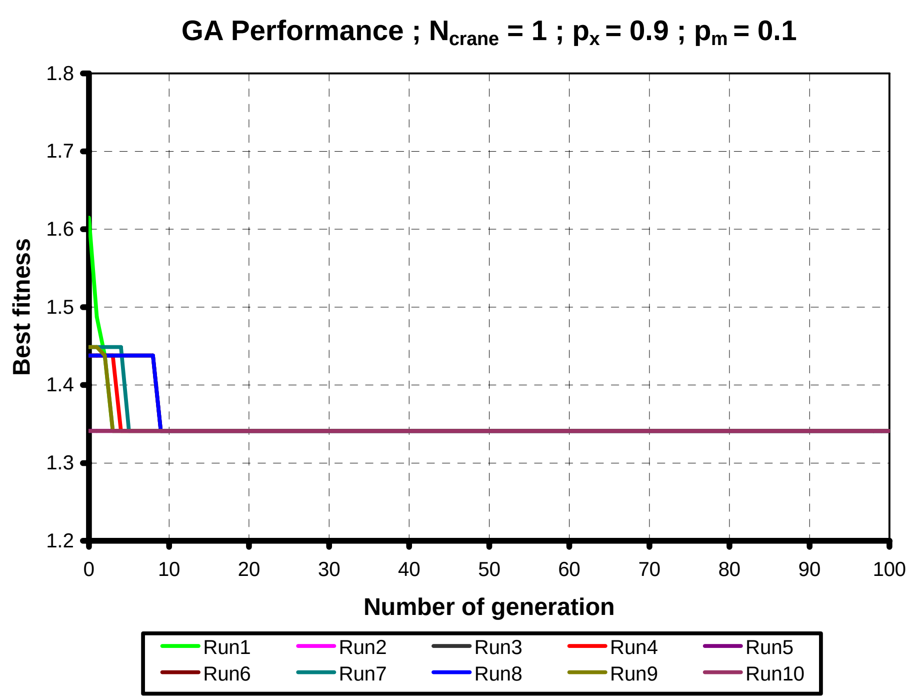


Figure 4.34: GA Performance in 10 Independent Runs of Number of Crane Test 1 Scenario 1 (N_{crane} = 1), P_x = 0.9

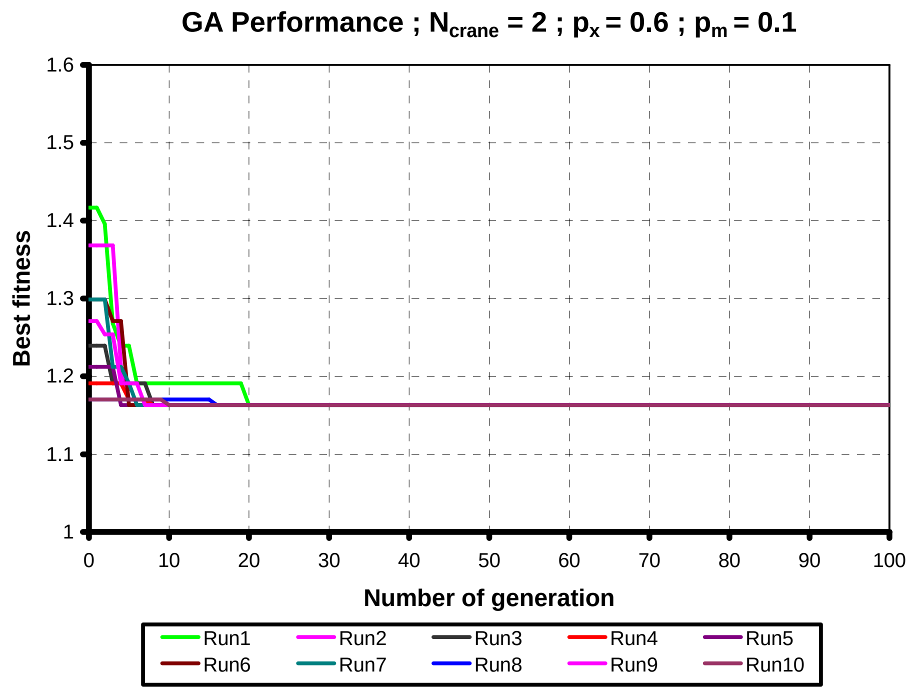


Figure 4.35: GA Performance in 10 Independent Runs of Number of Crane Test 1 Scenario 2 (N_{crane} = 2), P_x = 0.6

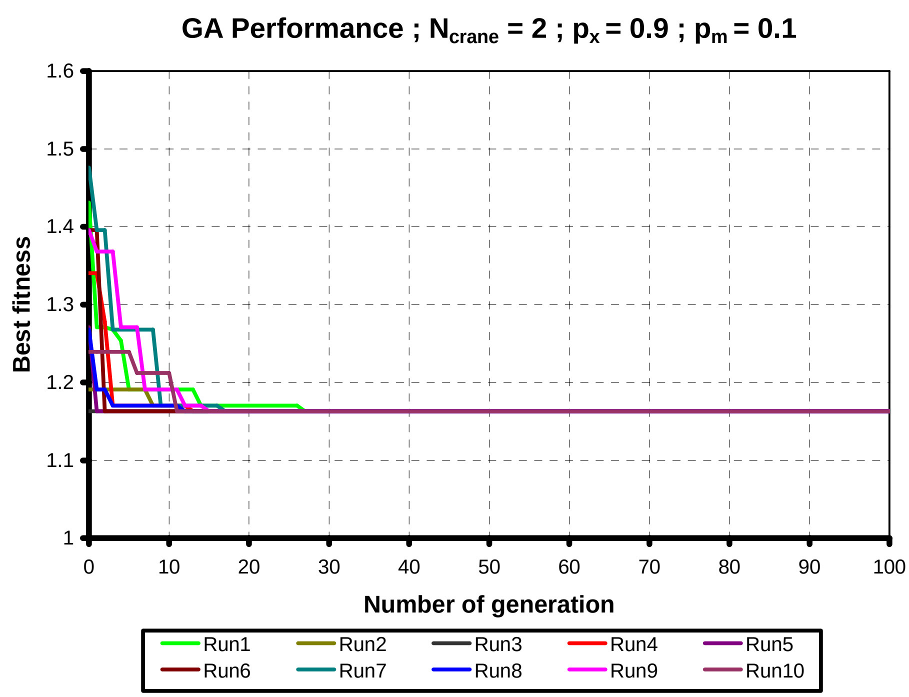


Figure 4.36: GA Performance in 10 Independent Runs of Number of Crane Test 1 Scenario 2 (N_{crane} = 2), P_x = 0.9

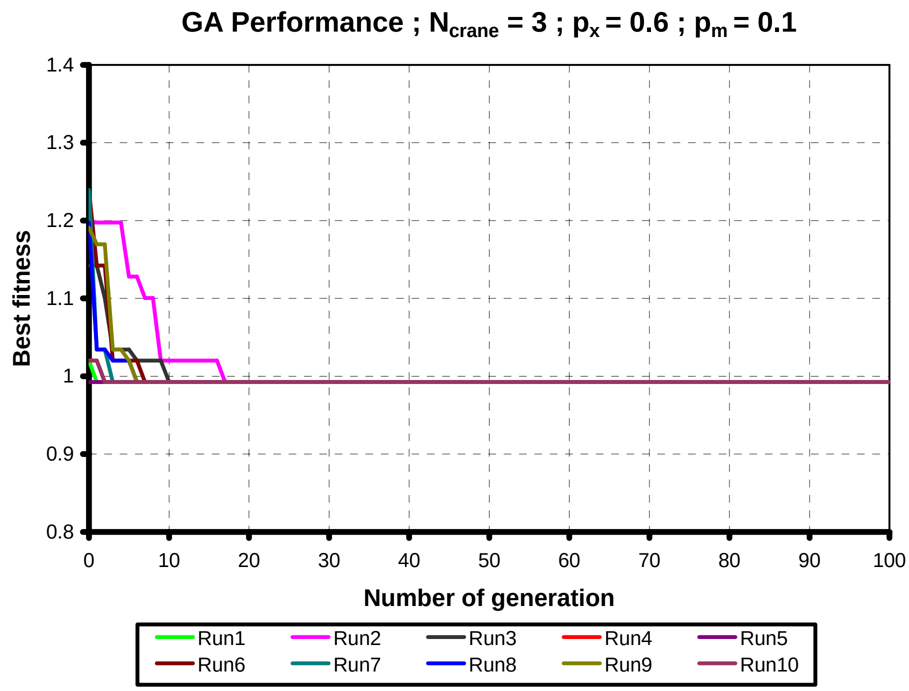


Figure 4.37: GA Performance in 10 Independent Runs of Number of Crane Test 1 Scenario 3 (N_{crane} = 3), P_x = 0.6

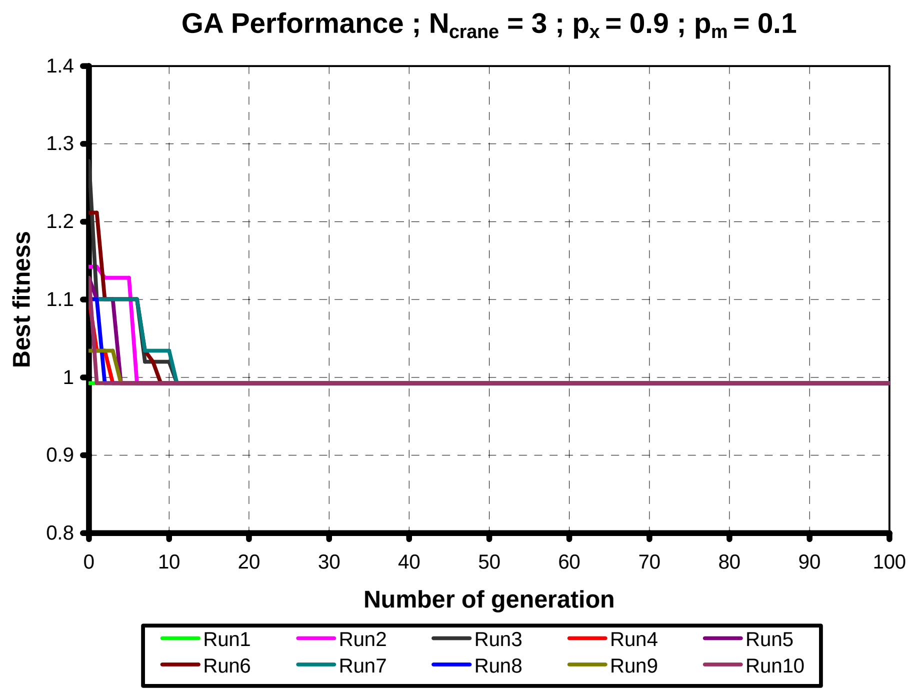


Figure 4.38: GA Performance in 10 Independent Runs of Number of Crane Test 1 Scenario 3 (N_{crane} = 3), P_x = 0.9

GA performance of the first series of tests – 3 batches request.

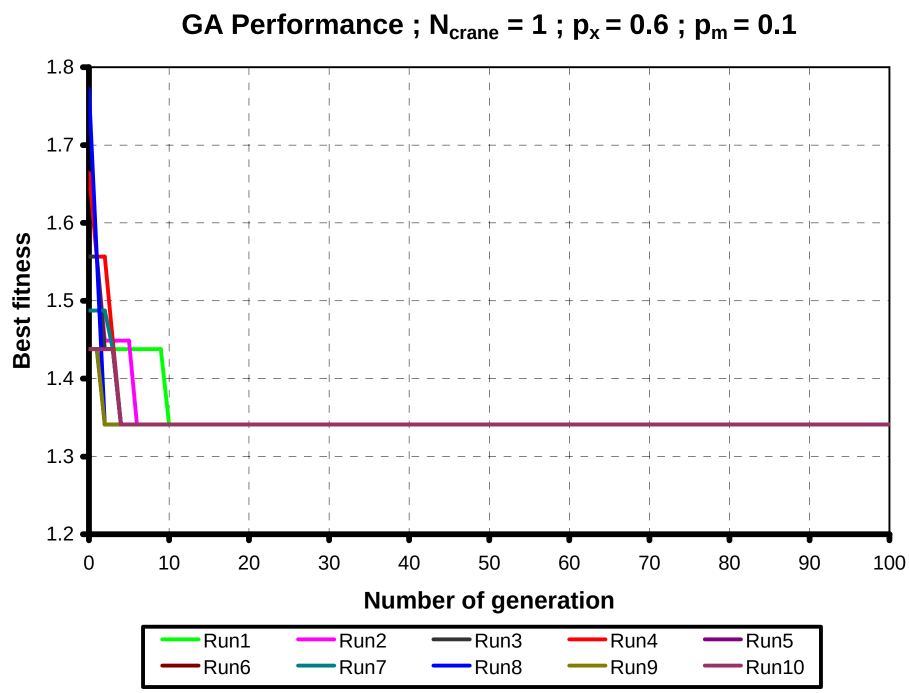


Figure 4.39: GA Performance in 10 Independent Runs of Number of Crane Test 2 Scenario 1 (N_{crane} = 1), P_x = 0.6

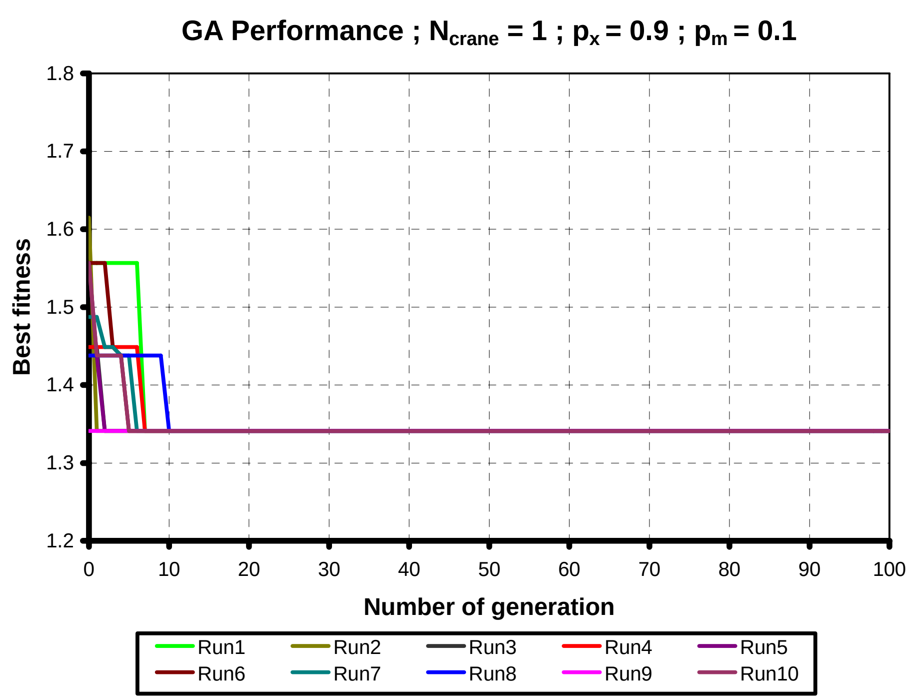


Figure 4.40: GA Performance in 10 Independent Runs of Number of Crane Test 2 Scenario 1 (N_{crane} = 1), P_x = 0.9

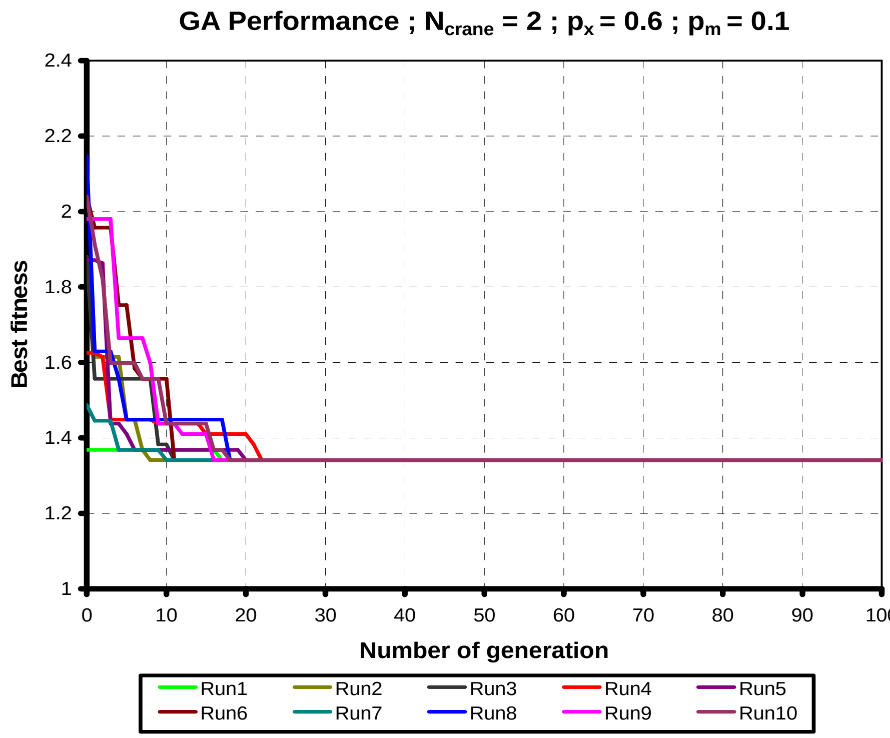


Figure 4.41: GA Performance in 10 Independent Runs of Number of Crane Test 2 Scenario 2 (N_{crane} = 2), P x = 0.6

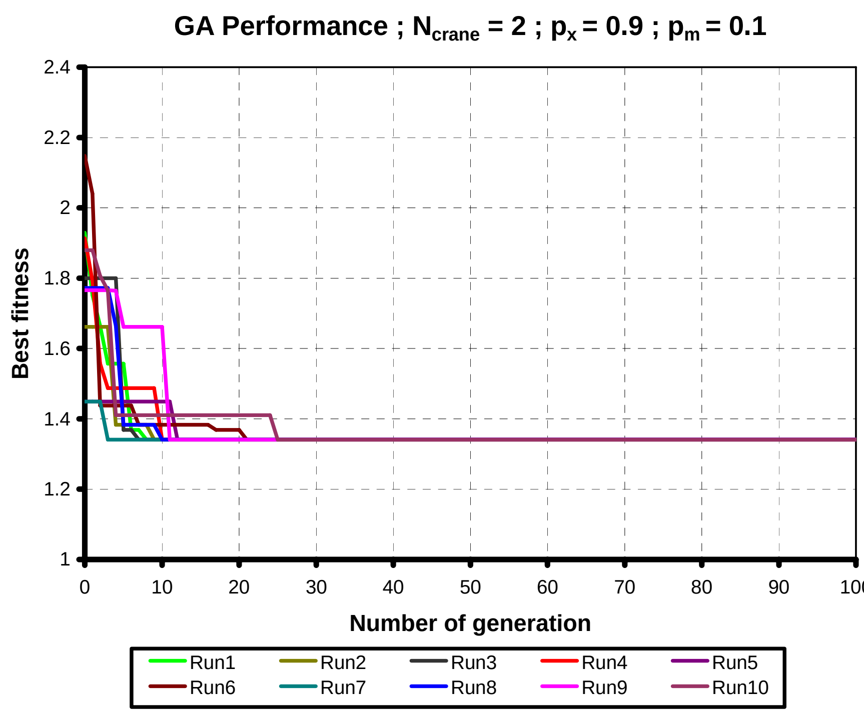


Figure 4.42: GA Performance in 10 Independent Runs of Number of Crane Test 2 Scenario 2 (N_{crane} = 2), P_x = 0.9

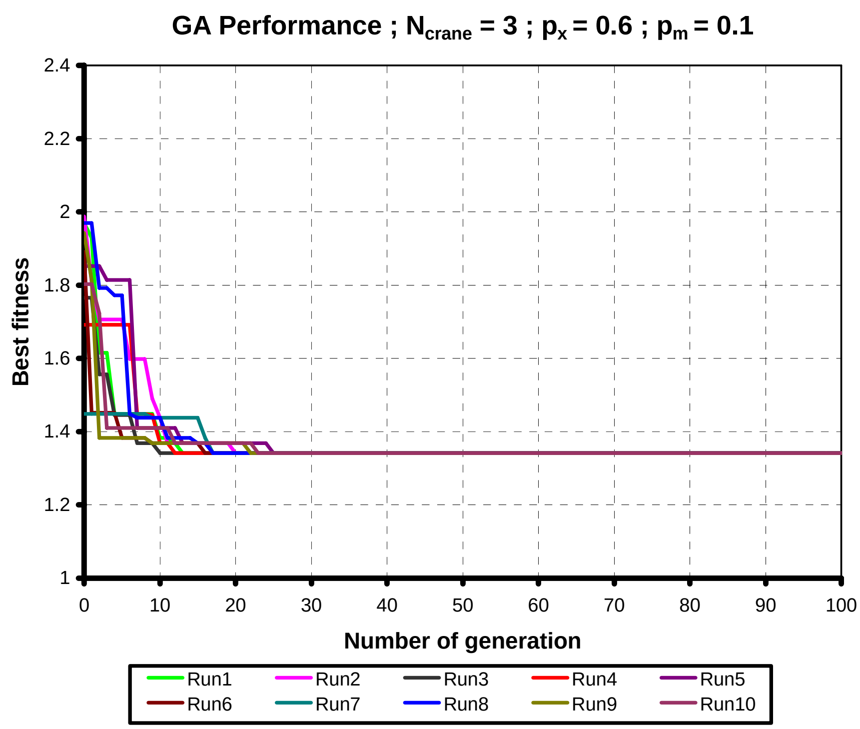


Figure 4.43: GA Performance in 10 Independent Runs of Number of Crane Test 2 Scenario 3 (N_{crane} = 3), P_x = 0.6

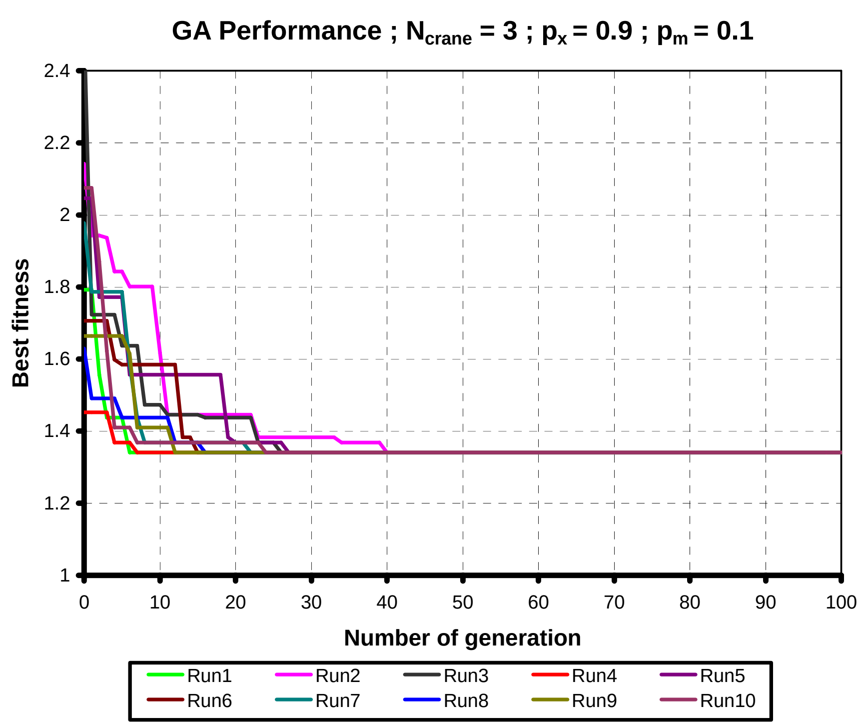


Figure 4.44: GA Performance in 10 Independent Runs of Number of Crane Test 2 Scenario 3 (N_{crane} = 3), P_x = 0.9

4.2.6.4 Recommended GA Parameters for CLP

For different GA operators as well as different type of problems, it is obvious that GA parameters should be tested through extensive experiments and adjusted for the best performance. In short, for CLP, the Steady State GA is used with those recommended parameters as in the table below.

Table 4.2: Default Parameters for CLP

Name of Genetic Operators/ Procedures/ Parameters	Probability/ Rate/ Value
Specialized Initialiser	NA
1 Point Combinational Crossover (OPMX and 1-PX)	0.9
Combinational Permutation Mutation	0.1
Population size = $L_{integer}$	$2*(N_{crane} + N_{small\_group})$
Roulette Wheel Selection and Worst Replacement Scheme	0.25

4.3 Strategy of Running the GA Model for CLP

Since the CLP model using GA technique as the optimizer, it has the GA's character of long running time. The strategic approach to solve this problem focuses on how to find a "reasonably good" (if not perfect) solution in a reasonable amount of time. This goal is related to maximizing on-line performance, since on-line performance will be maximized if high-fitness individuals are likely to be chosen at each step, including the last. From the experimental results, it can be seen that GA is able to find a very good solution, for example about 95% of the best solution results, in a relatively small number of generations. Main interests are then focused on how to find the best possible solution in as small as possible number of generations (to save the computational time). This is very critical for large scale CLP, since the evolving time of GA can be as long as hours to ensure the correct solution. The technique is to stop GA evolution when a "good enough" solution is achieved. The termination condition is either one of the 3 criteria below:

(1) The number of generations without improvement of the best solution: $N_{generations}^{best} = 100$

(2) The convergence ratio of the best solution and the worst solution in the current population: $Convergence \quad Ratio = \frac{\min}{\max} 100\% = 0.95$

(3) The total number of generations: $N_{generations}^{total} = 1000$

The default values of the three termination criteria are based on the experimental tests with the condition that the program should find a reasonable solution in less than 20 minutes. Three termination criteria are illustrated in Fig. 4.43.

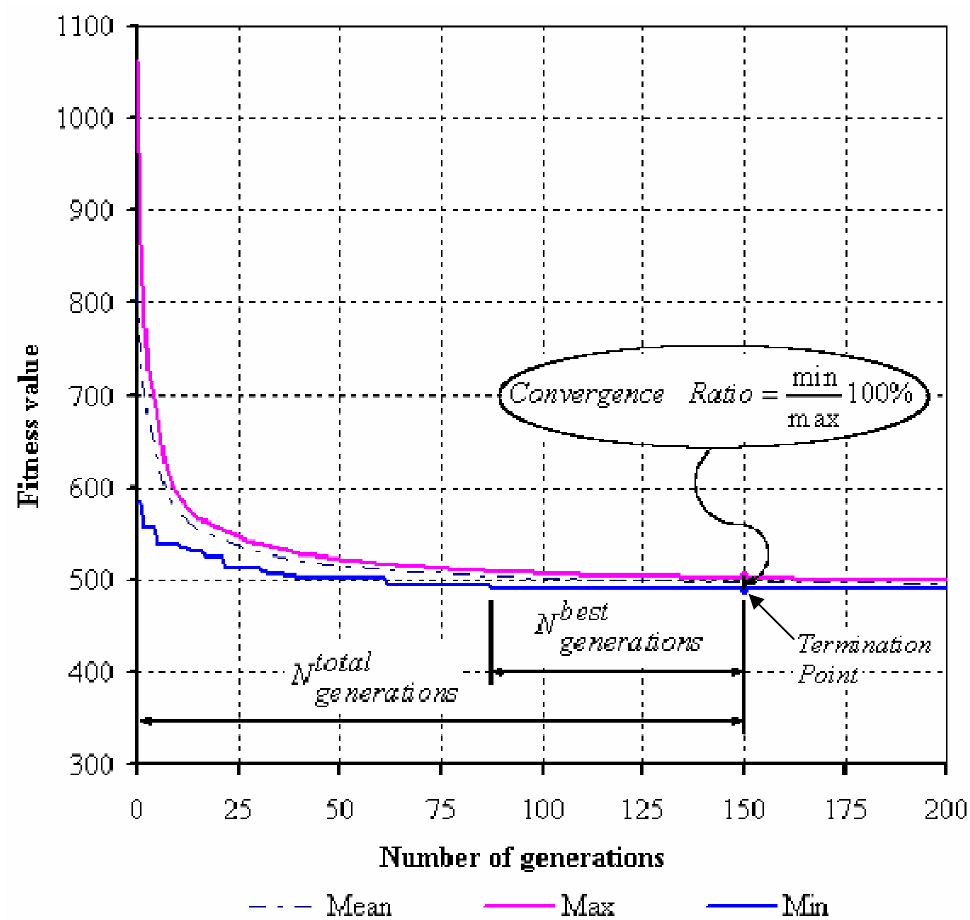


Figure 4.45: Illustration of Three Termination Criteria for GA Model

CHAPTER V: APPLICATIONS OF THE GA MODEL FOR CLP

5.1 Practical Applications of the GA Model for CLP

This chapter discusses the possible applications of the model as a design tool in the lift planning process. Some of these are presented in detail with illustrated examples.

5.1.1 Checking the Crane Capacity (R & Q) – Selection of the Crane Models

The GA model can be used to test the crane capacity for a group of lifted tasks based on the load radius curve of the crane, the weight of the total load for each task and the larger distance between the crane location and either the loading or the demanding position. The crane capacity constraints require the selected crane having enough reach and capacity for the assigned lifted jobs. If the crane does not have enough capacity for the jobs, for example its boom is so short that it cannot provide enough reach, or the crane‘s capacity is not high enough to raise the load at its relative reach, the crane will be given a penalty fitness (i.e. objective function value). The penalty fitness is high enough to ensure the under-capacity crane will be eliminated during evolutions. If all the available cranes are "rejected", the program will pose a screen message that says "Current cranes do not have enough capacity! Please use bigger cranes." In this case, the user is expected to add bigger capacity cranes to the database, or re-arrange the site facilities layout to reduce the reach requirement or disassemble the lifted module into smaller units to lower the load. The model will assign penalty fitness for the solutions with the disqualified crane (i.e. the crane either lacks the reach requirement according to eq. 4.22 or does not have enough capacity to handle the job according to eq. 4.23). The penalty fitness is disadvantageous enough to ensure those solutions (and the disqualified crane) are eliminate during the GA evolution (section 4.2.3.2). For the valid solutions, the model selects the best solution based on their fitness, which takes into account the different tower crane configurations such as the hoisting velocity of the hook, the radial velocity of the trolley, and the slewing velocity of the jib. Hence, it is not only capable of rejecting the disqualified cranes but also selecting the most suitable cranes among the available cranes.

The following examples show how the model reacts with different scenarios where the crane capacity constraints impose on the optimum solution. The site layout is described as in Fig. 5.1.

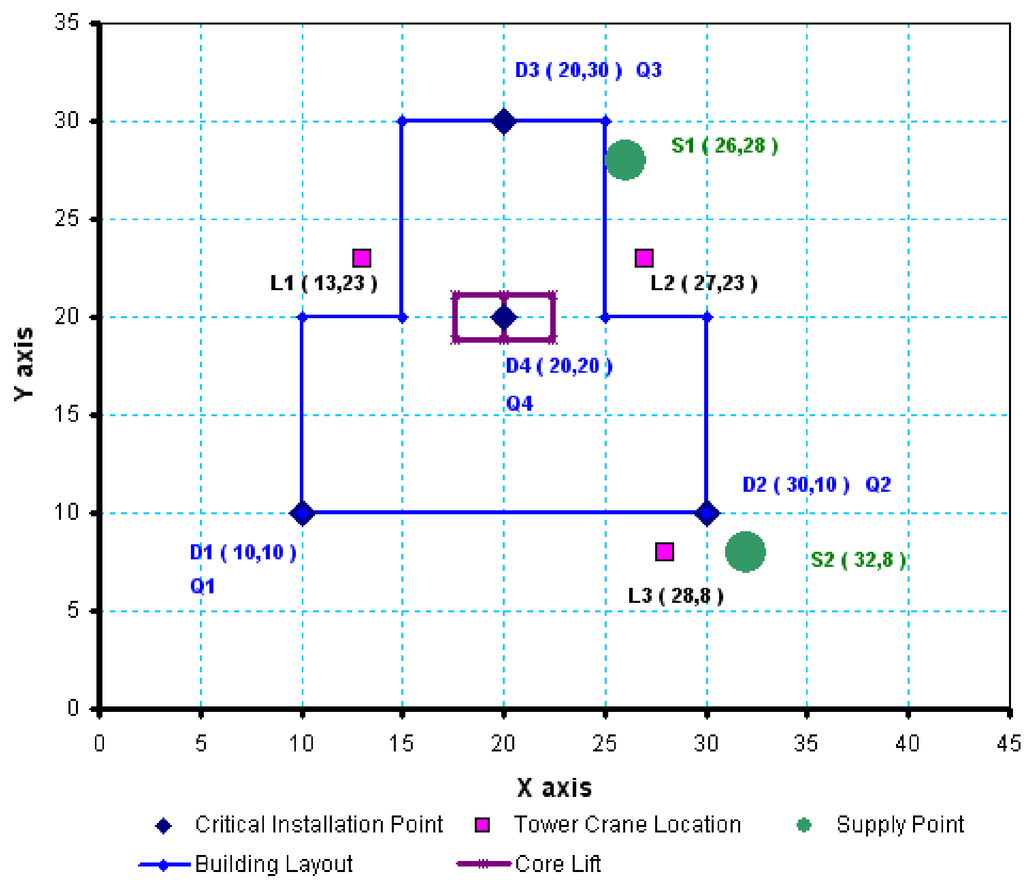


Figure 5.1: The Tower Crane Layout – Crane Capacity Tests

As can be seen in fig 5.1, there are only 4 main structures to install, namely the two columns at D_1 and D_2, a structural precast wall at D_3 and a core lift at the centre of the building D_4. After considerations of other site constraints and factors, there are three possible locations for the tower crane, and two possible supply points for the tower crane used. Only one tower crane will perform all the 4 lifted tasks. Since there is only one crane in the site, the CLP in this case is as simple as: (1) where to locate the crane; (2) where to locate the precast element; (3) what is the safe lift sequence if the installation order of the 4 lifted tasks are the same. The only one tower crane has its capacity as in Fig. 5.2.

Capacity	
R (m)	Q (ton)
5	12
10	12
15	10
20	8
25	6.5
30	5.5
35	4.8
40	4.2
45	3.8
50	3.5

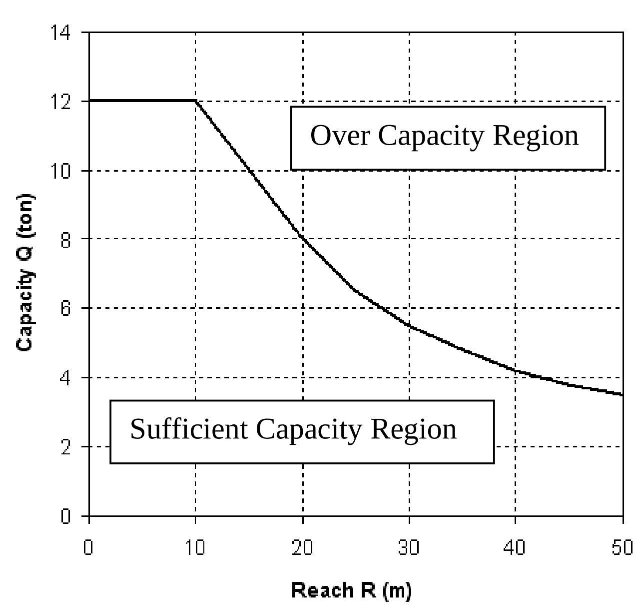


Figure 5.2 Load Radius Curve – Crane Capacity

The test is implemented with different scenarios in order to test GA results. It can be seen that the reach requirement of the crane is satisfied since the building size is relatively small in comparison to the available boom length (50 meters). Hence, different scenarios are created by controlling the weight of the lifted modules such that the solutions can be recognized and evaluated. Five scenarios are tested below.

<u>*Scenario 1:*</u> "Free running scheme". The weight of the four elements are $Q_1 = Q_2 = 4$ ton, $Q_3 = 6$ ton, and $Q_4 = 8$ ton, accordingly. According to the load radius curve of the crane, any crane location of the three possible ones can be chosen to handle the

four jobs. If the L_1 is chosen, there is a restriction for the lifted module 4 (the core lift) to be delivered at supply point S_1. It is because the crane capacity at the radius of 24.207 m (the distance between L_1 and S_2) is less than 6.7 ton while Q_4 = 8 ton.

Scenario 2: "L_1 & L_3 restricted scheme". The weight of the four elements are Q_1 = 4 ton, Q_2 = 4 ton, Q_3 = 6 ton, and Q_4 = 11.5 ton, accordingly. Only crane location L_2 is appropriate to be chosen.

Scenario 3: "L_1 & L_2 restricted scheme". The weight of the four elements are Q_1 = 4 ton, Q_2 = 10.8 ton, Q_3 = 6 ton, and Q_4 = 7.5 ton, accordingly. Only crane location L_3 is appropriate to be chosen.

Scenario 4: "L_1 & L_2 restricted scheme with an increase in the weight Q_4". The weight of the four elements are Q_1 = 4 ton, Q_2 = 10.8 ton, Q_3 = 6 ton, and Q_4 = 10 ton, accordingly. Only crane location L_3 is appropriate to be chosen. Moreover, since Q_4 has increased from 7.5 to 10 ton, it cannot be delivered at the supply point S_1 as in scenario 3.

Scenario 5: "No solution scheme". The weight of the four elements are Q_1 = 4 ton, Q_2 = 10.8 ton, Q_3 = 6 ton, and Q_4 = 11 ton, accordingly. From the load radius curve, the existing crane does not have enough capacity to lift the tasks.

GA test is conducted with $P_x = 0.9$, $P_{mut} = 0.5$, $P_{replace} = 0.25$, $N_{pop} = 10$ and $N_{generations}^{total} = 50$. A summary of the test results are presented in table 5.1.

Table 5.1: Summary Results of the Crane Capacity Test in Scenarios 1 to 4

Scenario	**1**	**2**	**3**	**4**
	Tower Crane Location Chosen			
Crane 1	$\mathbf{L_1}$	$\mathbf{L_2}$	$\mathbf{L_3}$	$\mathbf{L_3}$
	Q (ton) - Supply Point Chosen – Lifting Sequence			
Lifted Module 1	4 – S_2 – 1	4 – S_2 – 3	4 – S_1 – 1	4 – S_1 – 4
Lifted Module 2	4 – S_1 – 2	4 – S_2 – 4	10.8 – S_2 – 2	10.8 – S_2 – 1
Lifted Module 3	6 – S_1 – 4	6 – S_2 – 1	6 – S_1 – 4	6 – S_1 – 2
Lifted Module 4	8 – S_1 – 3	11.5 – S_1 – 2	7.5 – S_1 – 3	10 – S_2 - 3
Fitness (minute)	**3.0**	**3.15**	**3.18**	**3.39**

The optimised tower crane layouts in the tests are illustrated in figures below.

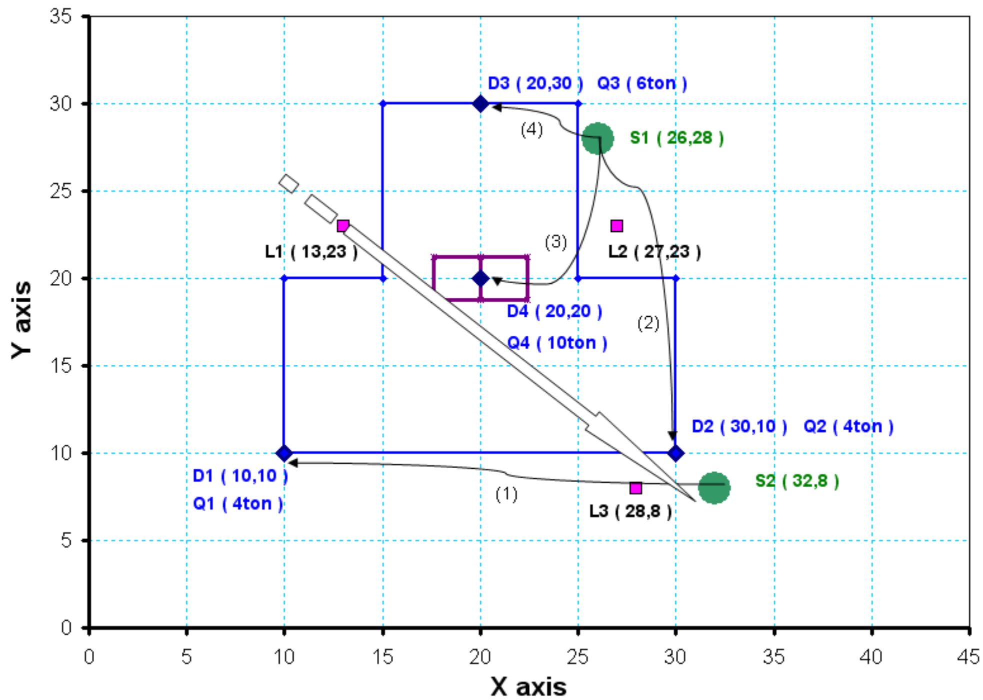


Figure 5.3: Results of the Optimised Tower Crane Layout – Scenario 1, Crane Capacity Tests

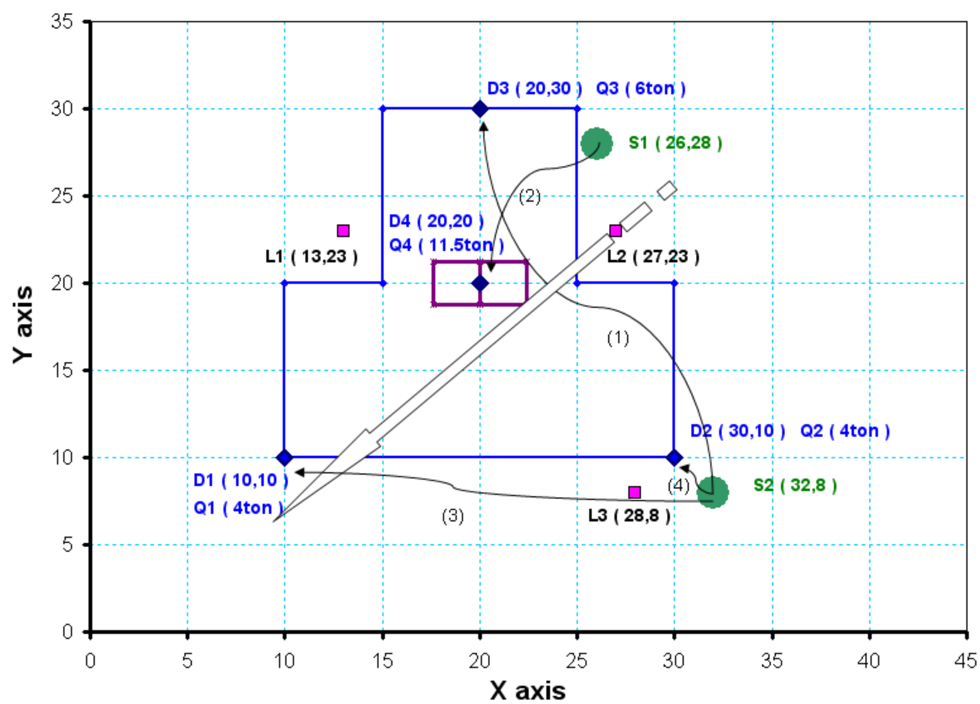


Figure 5.4: Results of the Optimised Tower Crane Layout – Scenario 2, Crane Capacity Tests

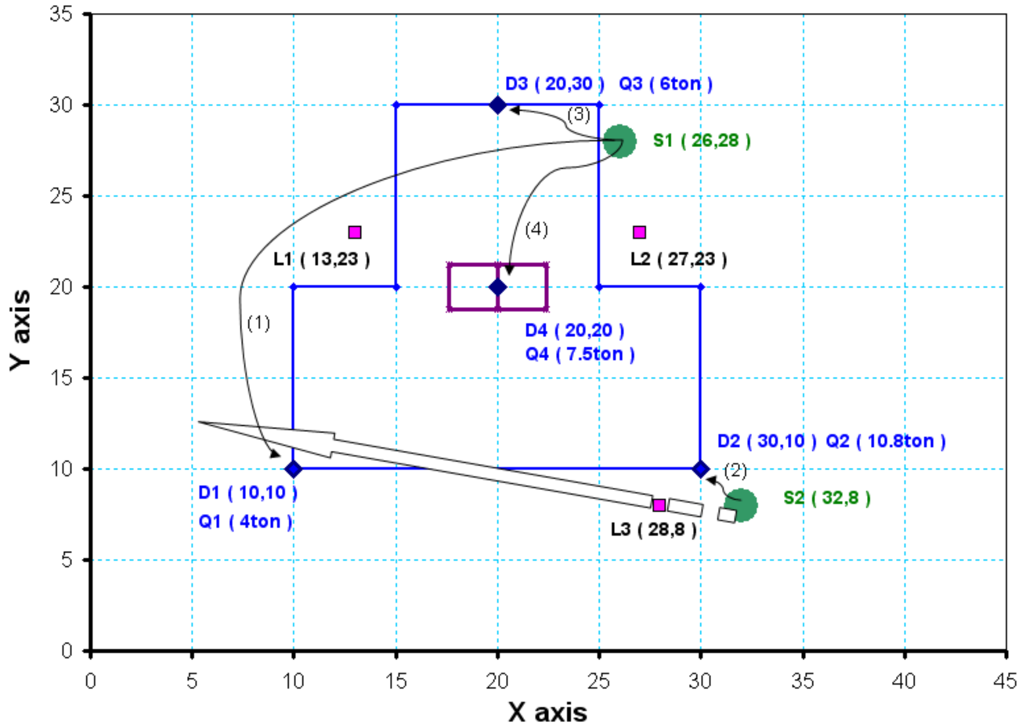


Figure 5.5: Results of the Optimised Tower Crane Layout – Scenario 3, Crane Capacity Tests

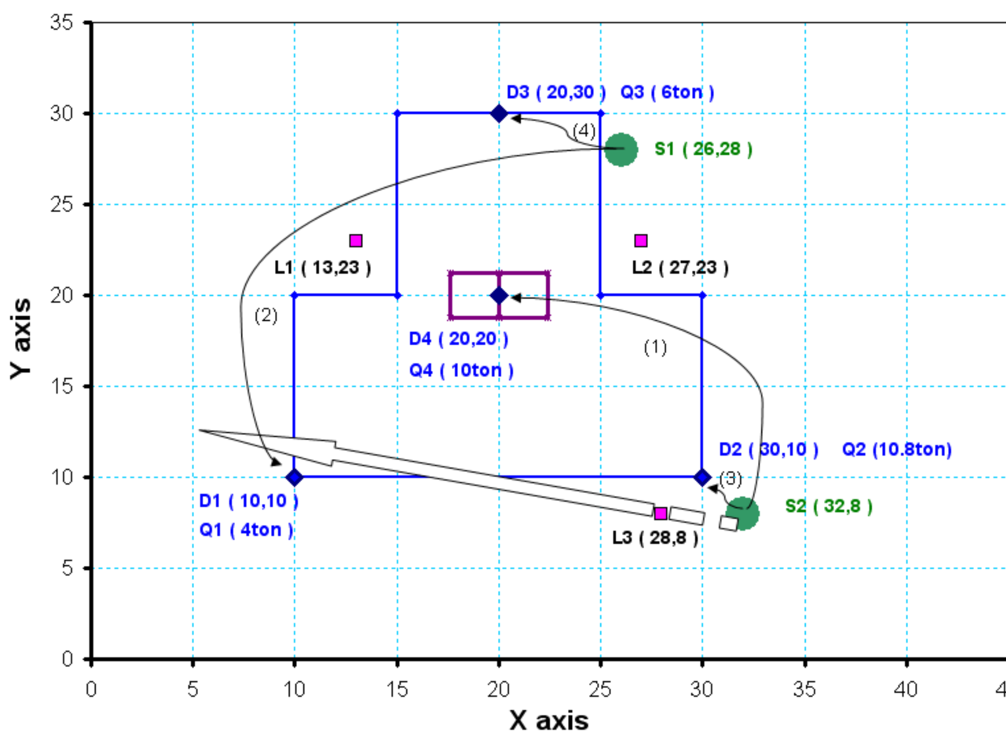


Figure 5.6: Results of the Optimised Tower Crane Layout – Scenario 4, Crane Capacity Tests

The checking of the tower crane capacity for those four optimal solutions in each scenario is highlighted in figures 5.7 to 5.11 below.

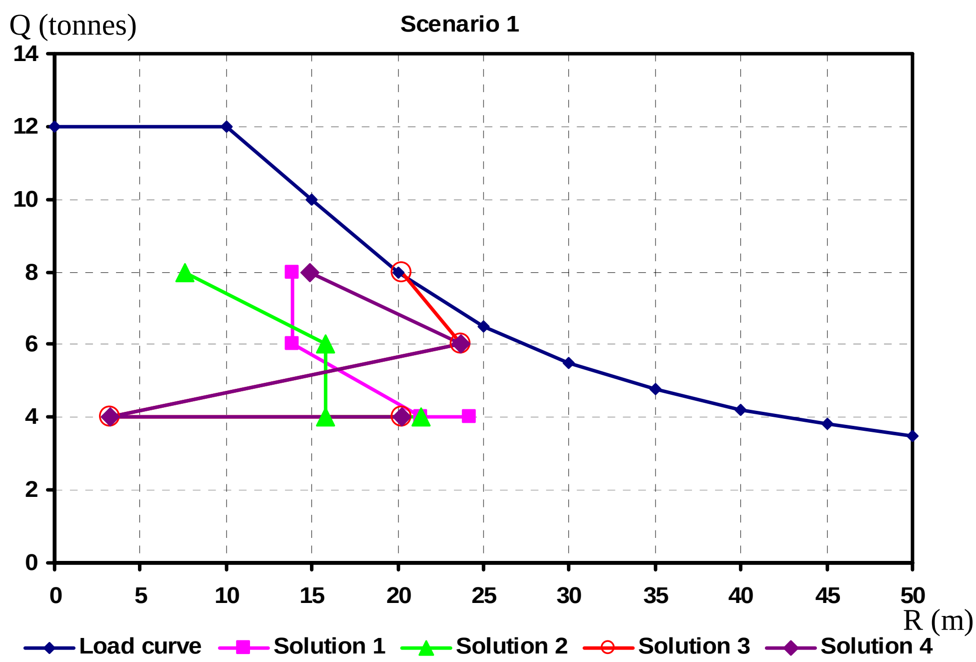


Figure 5.7: Checking for the Tower Crane Capacity – Scenario 1, Crane Capacity Tests

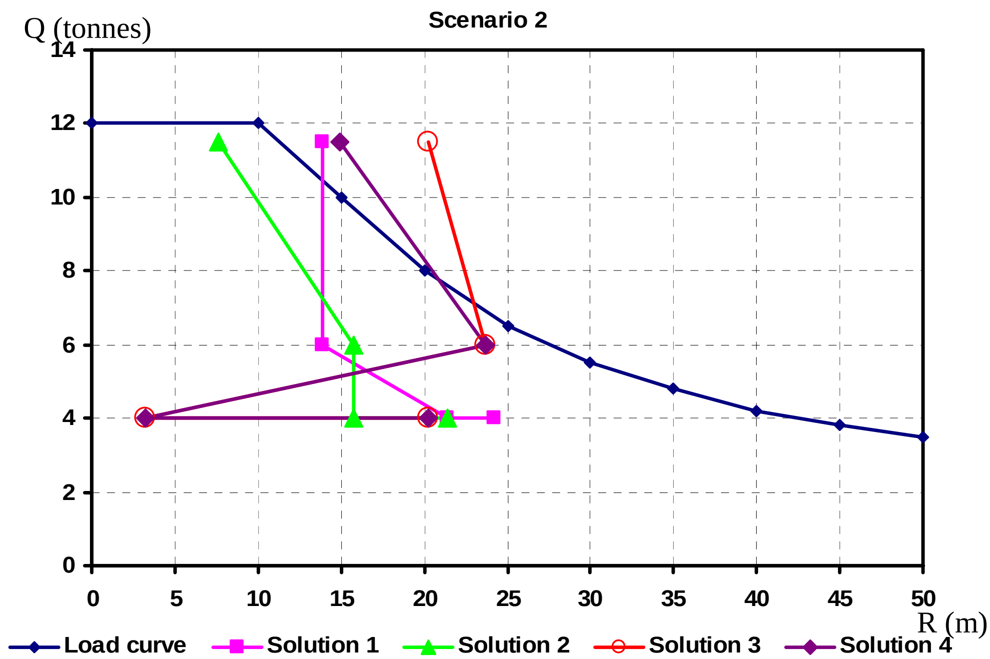


Figure 5.8: Checking for the Tower Crane Capacity – Scenario 2, Crane Capacity Tests

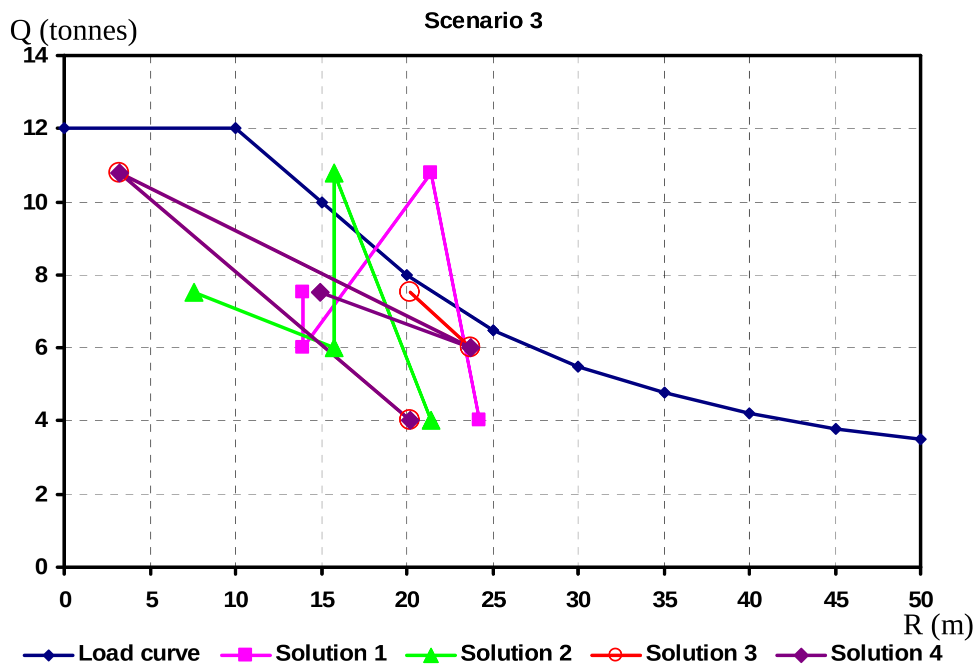


Figure 5.9: Checking for the Tower Crane Capacity – Scenario 3, Crane Capacity Tests

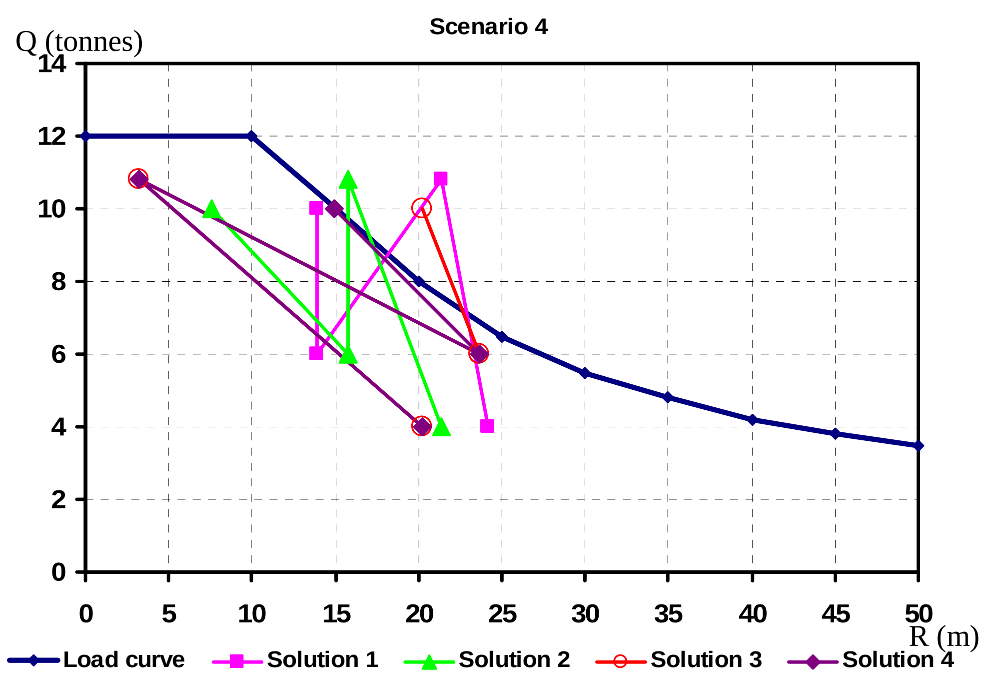


Figure 5.10: Checking for the Tower Crane Capacity – Scenario 4, Crane Capacity Tests

In Fig. 5.7, all the solutions satisfy the crane capacity constraints. The program chooses the best solution based on its fitness. Solution 1 is chosen since it has the minimum hoisting time. On the other hand, in Fig. 5.8, while most of the solutions violate the crane capacity constraints, only solution 2 satisfies these constraints. In Fig. 5.9, there are two solutions 3 and 4 which satisfy these constraints. Solution 3 is chosen since it has the smaller hoisting time. In Fig. 5.10, only solution 4 satisfies barely the constraints thus it is chosen. It should be noted that the four solutions discussed above are not all the possible solutions of this example, but are among the best ones of each scenario. The objective function of the GA model involves many complex equations to calculate distances, angles, different components of the hoisting time, interpolation of the load radius curve of the crane capacity and especially the function to choose the safe lifting sequence. Therefore, it is difficult to check all the possible solutions (192 as in this small example) to affirm the found solution in each scenario is indeed the optimal solution in all over the search space. For the purpose of testing the generated solutions of the GA model, the tests are conducted many times, and with a large number of generations. The consistent results of GA model in different runs and its efforts to locate the optimal solution in each scenario are highlighted in Fig. 5.12.

In scenario 5, the GA model cannot find a valid solution and it generates an sample output as in Fig. 5.11.

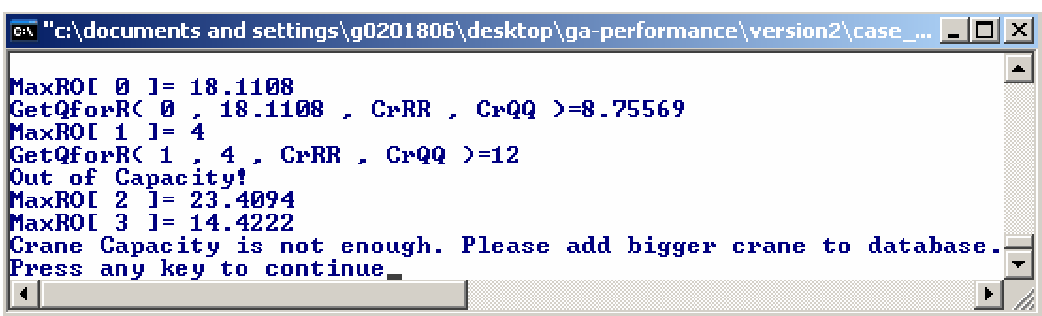


Figure 5.11: No Solution Available – Scenario 5, Crane Capacity Tests

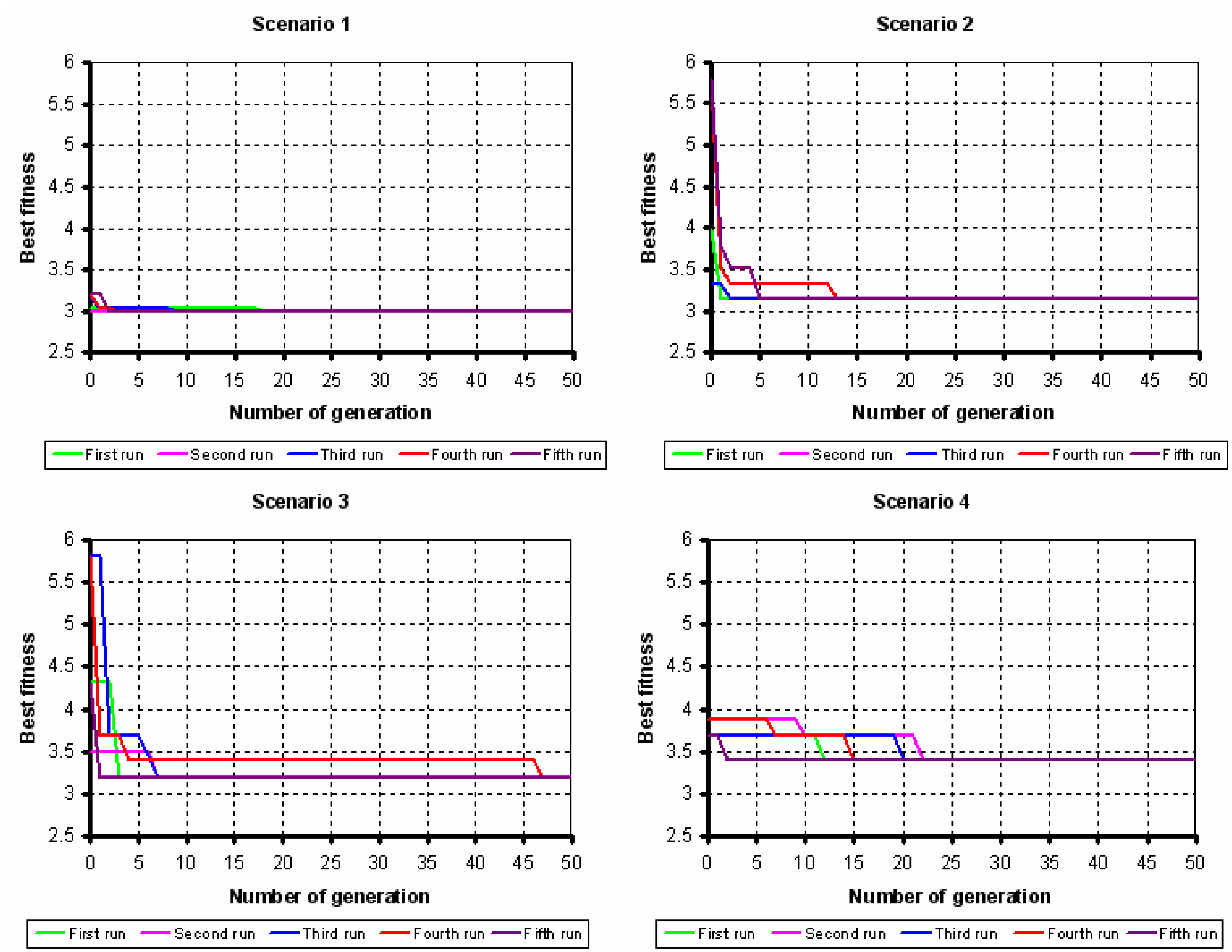


Figure 5.12: GA Performance in 5 Independent Runs of Each Scenario from 1 to 4 - Crane Capacity Tests

Some interesting findings from the results of crane capacity tests are drawn below. First, the GA model gave favourable and consistent results in 5 independent tests within only 50 generations. Since the site layout (including the installation locations, the tower crane locations and the supply point locations) and the tower crane configurations are the same; the fitness values of those tests are comparable. The best result is found in scenario 1 with the value of hoisting time of 3.00 minutes. The constraints are imposed more severely in the subsequent scenarios 2, 3, and 4. As a result, the GA model found the longer hoisting time of 3.15, 3.18, and 3.39 minutes, respectively. This is logical since the best solution in previous scenario violates the more severe constraints in the new scenario (see Fig. 5.7 to 5.10) and thus is rejected.

Secondly, it seems that the GA model works for precast installations as effectively as the model of Zhang et al., (1995) in the cast in-situ concrete construction. To highlight the effectiveness of the GA model, the results obtained are compared with the fitness value of 4.31 minutes (one of the common values of the hoisting time found during the GA evolution of the four scenarios). If the solution with that fitness value is chosen in real practice, the optimal solution in each scenario may save as much as 43 % in scenario 1 to at least 27 % in scenarios 4. According to Zhang et al. (1995), their model can save from 20 to 40% of the horizontal hoisting time.

Lastly, the more constraints about crane capacity, the harder the GA model is to find the best solution. While GA model found the best solution in scenario 1 after average of 2.2 generations, it took an average of 5.6, 13.2 and 14.2 generations in scenario 2, 3, and 4 respectively (from Fig. 5.12). This can be explained by the sparseness of the solution space as discussed in section 3.4.3.

5.1.2 Testing the Symmetric Layout

One of the most important issues is to ensure the GA model exhaustively find the best solution all over the search space. The test series of the symmetric layout can prove the performance of GA model. In the symmetric layout problems, there will be at least 2 symmetric solutions. How the model behaves in such cases? How it can recognize the symmetric solutions? The performance of GA model is also illustrated in how often it finds one of those symmetric solutions as compared to others. If the GA model can find symmetric solutions in relatively equal number of independent runs, it might show that the genetic search mechanism works well all over the search space.

The test is implemented with 4 different scenarios in order to test GA results. Different scenarios are created by controlling the number of supply points and their locations such that the symmetric solutions can be recognized and tested. The scenarios chosen highlight either the symmetric or non-symmetric layout of crane locations and/or supply point locations. The site lay out is described in Fig. 5.13.

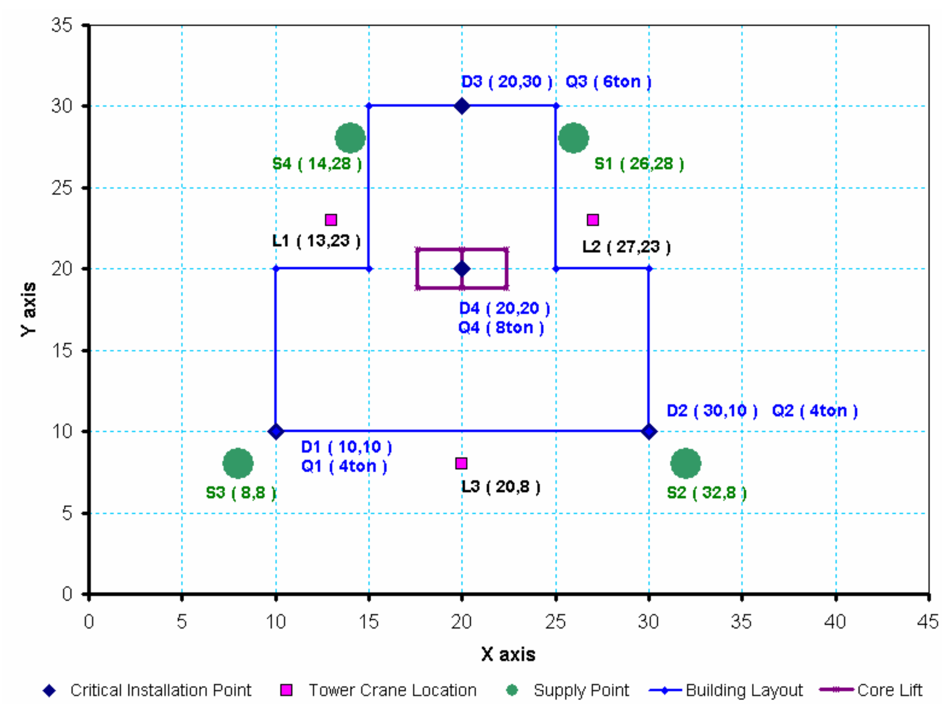


Figure 5.13: The Tower Crane Layout – Symmetric Layout Tests

GA tests are conducted with P_x = 0.9, P_{mut} = 0.5, $P_{replace}$ = 0.25, N_{pop} = 10 and $N^{total}_{generations}$ = 50.

<u>*Scenario 1:*</u> Symmetric layout test. In this scenario, there are 3 possible crane locations, 4 lifted modules and 4 supply points. They all share a vertical line of symmetry. The test results are summarised in table 5.2 and illustrated in Fig. 5.14.

Table 5.2: Summary Results of Two Symmetric Solutions – Scenario 1

Solution	**1**	**2**
	Tower Crane Location Chosen	
Crane 1	**L_3**	**L_3**
	Supply Point Chosen – Lifting Sequence	
Lifted Module 1	S_3 – 2	S_1 – 1
Lifted Module 2	S_4 – 4	S_2 – 4
Lifted Module 3	S_1 – 3	S_4 – 3
Lifted Module 4	S_2 – 1	S_3 – 2
Fitness (minute)	**2.78**	**2.78**

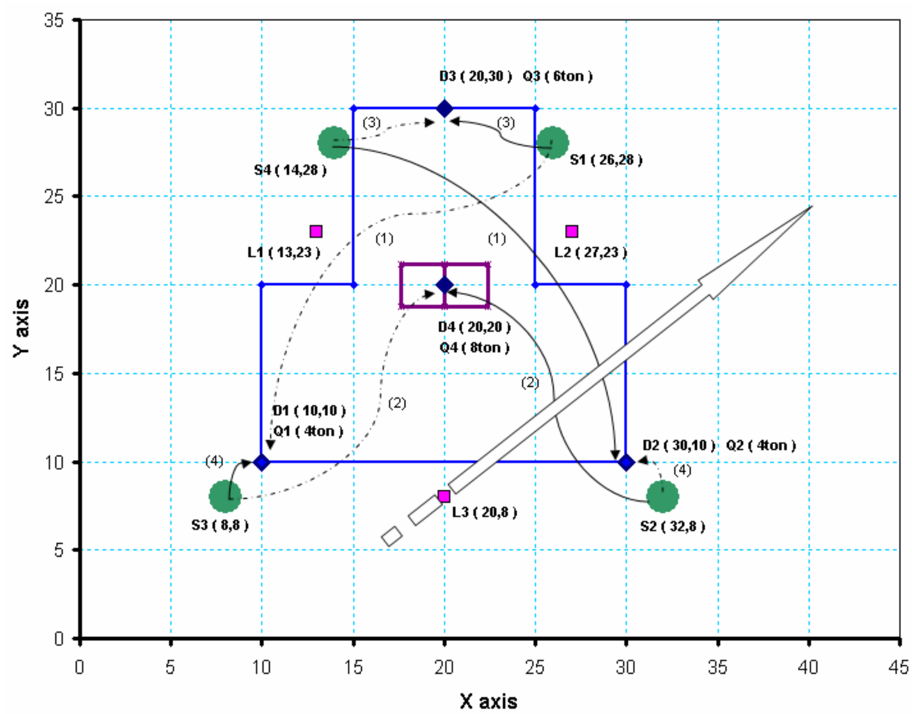


Figure 5.14: Results of the Optimised Tower Crane Layout – Scenario 1, Symmetric Layout Tests

GA model found the first solution (illustrated by continuous line) 3 times in 5 independent runs and the alternative solution (illustrated by centre line) 2 times in 5 independent runs of the scenario 1 (see Fig. 5.18)

Scenario 2: Non-symmetric layout test. In this scenario, there are 3 possible crane locations, 4 lifted modules and 3 supply points. The crane locations and demand points share a vertical line of symmetry. The results are non-symmetric.

The location L_3 governs with the total hoisting time of 2.78 minutes.

The lifted assignment policies are that lifted module 1 & 3 are delivered at supply point S_1, lifted module 2 & 4 at S_2 & S_3 respectively. The recommended lift sequence is 1-4-3-2 as illustrated in Fig. 5.15.

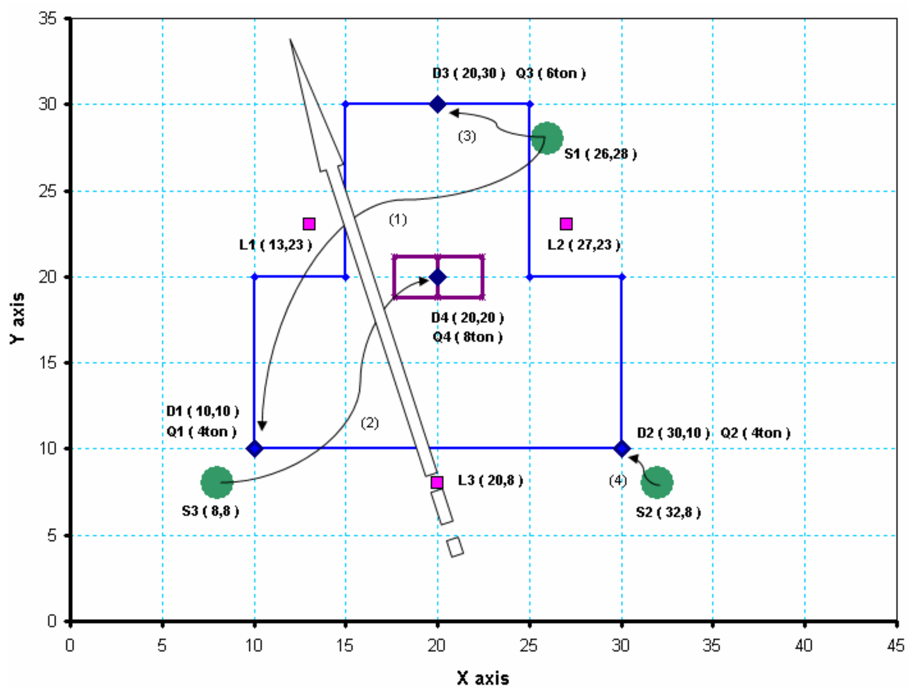


Figure 5.15: Results of the Optimised Tower Crane Layout – Scenario 2, Symmetric Layout Tests

Scenario 3: Symmetric layout test. In this scenario, there are 2 possible crane locations (exclude L3), 4 lifted modules and 4 supply points. Supply points, crane locations and demand points share the same vertical line of symmetry.

The test results are summarised in table 5.3 and illustrated in Fig. 5.16.

Table 5.3: Summary Results of Two Symmetric Solutions – Scenario 3

Solution	**1**	**2**
	Tower Crane Location Chosen	
Crane 1	**L_2**	**L_1**
	Supply Point Chosen – Lifting Sequence	
Lifted Module 1	$S_2 - 2$	$S_1 - 1$
Lifted Module 2	$S_4 - 1$	$S_3 - 2$
Lifted Module 3	$S_4 - 4$	$S_1 - 4$
Lifted Module 4	$S_4 - 3$	$S_1 - 3$
Fitness (minute)	**2.83**	**2.83**

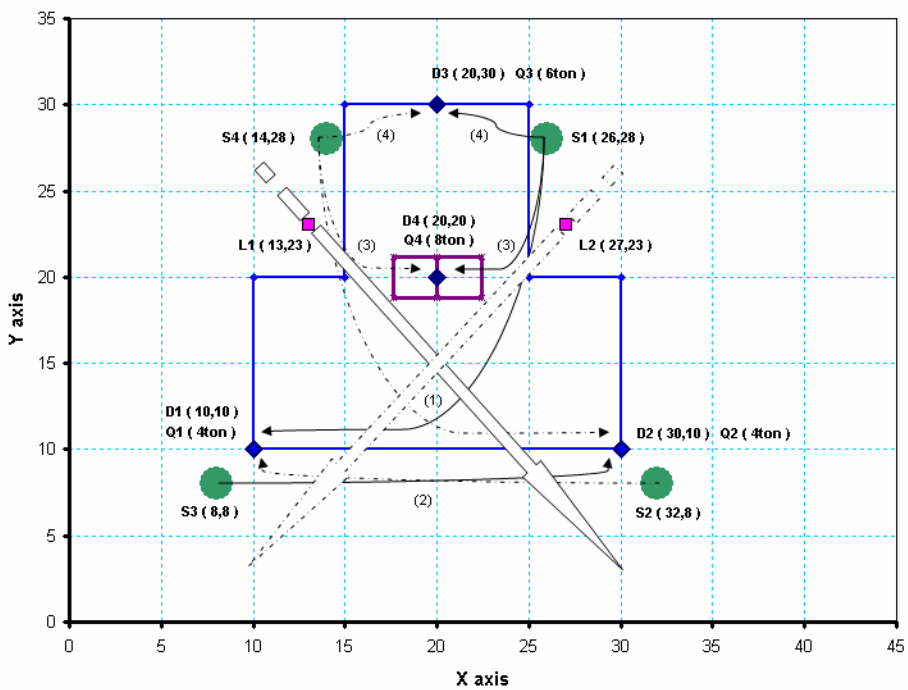


Figure 5.16: Results of the Optimised Tower Crane Layout – Scenario 3, Symmetric Layout Tests

GA model found the first solution (centre line) 4 times in 10 independent runs and the alternative solution (continuous line) 3 times in 10 independent runs of the scenario 3. In the other 3 runs, the best solutions have not been found yet (see Fig. 5.18).

<u>*Scenario 4:*</u> Non-symmetric layout test. In this scenario, there are 3 possible crane locations, 4 lifted modules and 2 supply points. The crane locations and demand points share the same vertical line of symmetry. The results are non-symmetric.

The location L_1 governs with the total hoisting time of 2.83 minutes.

The lifted assignment policies are that lifted module 2 is delivered at supply point S_3, the rest at supply point S_1. The recommended lift sequence is 1-2-4-3 as illustrated in Fig. 5.17.

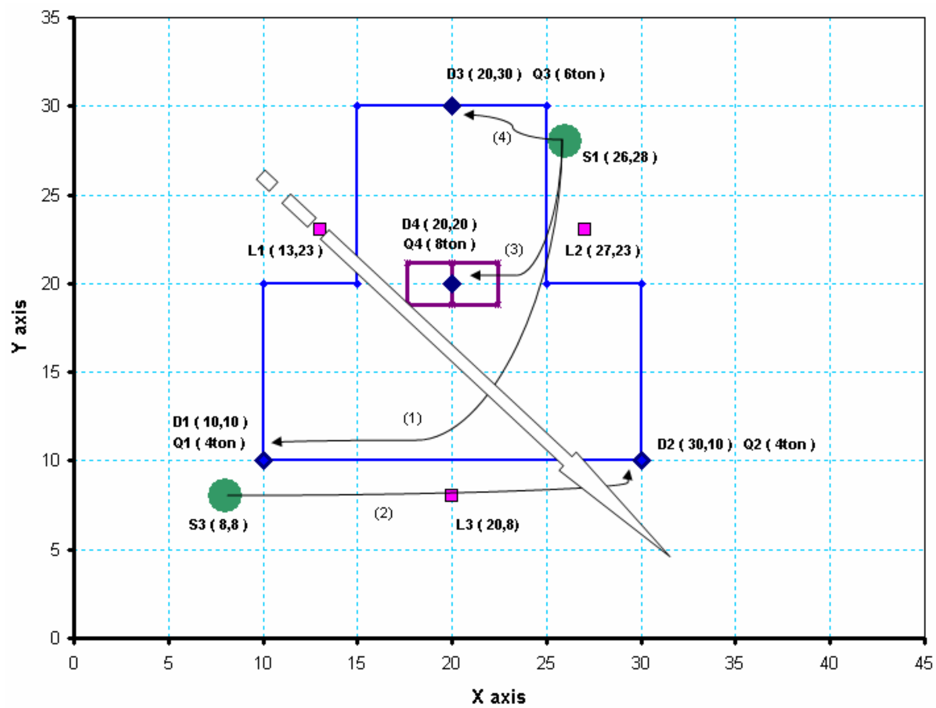


Figure 5.17: Results of the Optimised Tower Crane Layout – Scenario 4, Symmetric Layout Tests

This test was meant to check if given non-symmetric supply points, the GA returns the exact solution as in the scenario 3 solution. In scenario 3, when all the supply points, crane locations and installation points are symmetric, there are two symmetrical solutions. In this scenario, we restrict 2 out of 4 supply points, and then only 1 solution from the above scenario survives. The GA performances of 4 scenarios of symmetric test series are gathered in Fig. 5.18.

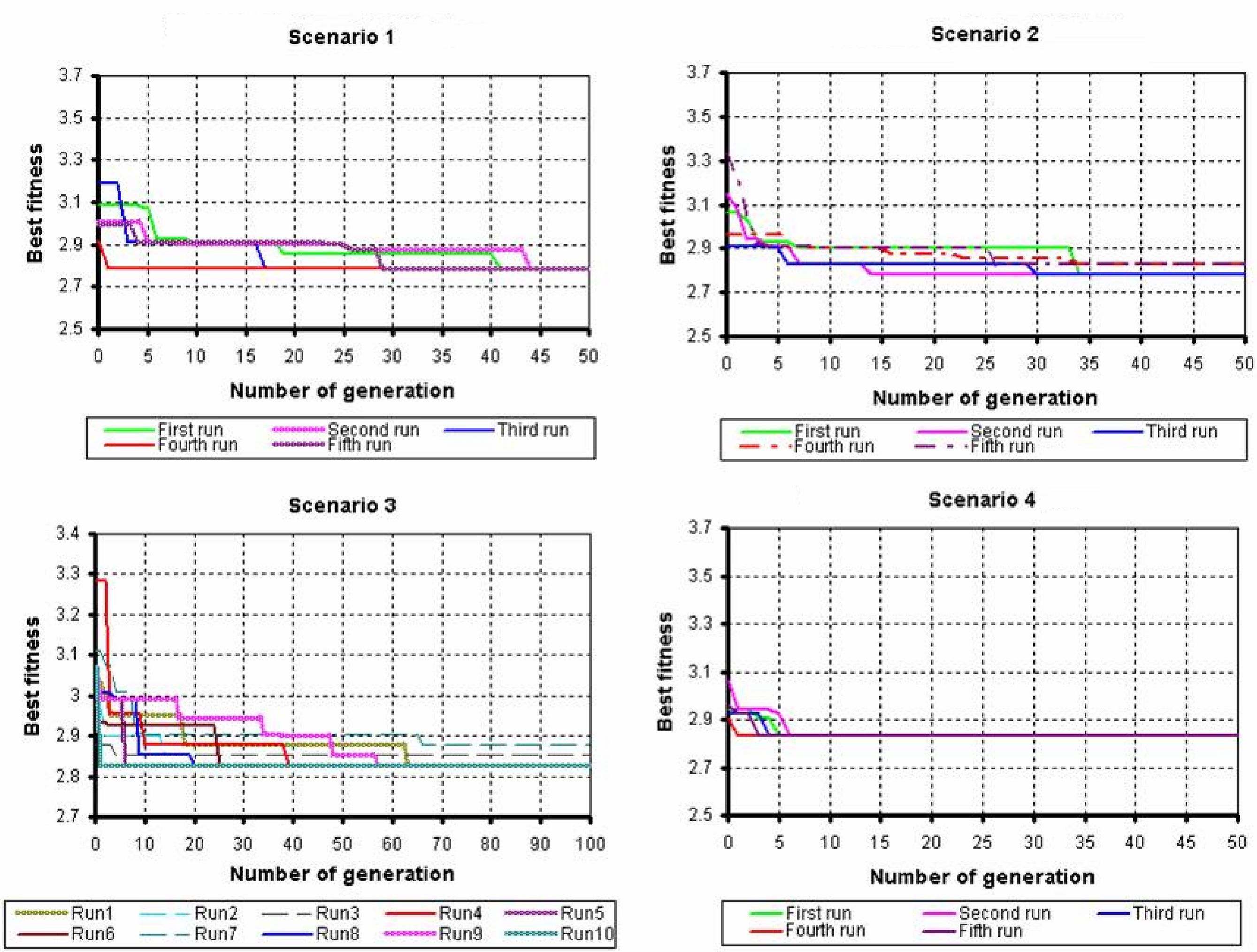


Figure 5.18: GA Performance in Independent Runs of Each Scenario from 1 to 4 – Symmetric Layout Tests

From the test results, it can be seen that the GA model can distinguish symmetric solutions in different runs. The number of runs that found symmetric solutions is relatively equal. For example, in 5 independent runs of scenario 1, GA model found the first solution 3 times (the 1st, 3rd and 4th run) and the alternative solution 2 times (the 2nd and the 5th) as in Fig. 5.14 – scenario 1. Alternatively, in 10 independent runs of scenario 3, GA model found the first solution 4 times (the 1st, 5th, 9th and 10th run) and the alternative solution 3 times (the 4th, 6th and 8th) as in Fig. 5.14 – scenarios 3.

From this series of tests, we can see other features of GA model that its performance is closely related to the ratio of the number of optimal solutions and the search space. For example, in scenario 2, the search space is smaller (less than one supply point) compared to scenario 1, however, GA performance in scenario 1 is better since their possible solution is double as in scenario 2 thanks to the symmetric solutions. In the symmetric case, GA model can be easier to find a good prototype of chromosome to exploit and then find the optimal solutions.

The number of optimal solutions may be larger than one, for example, in symmetric solutions there are at least two optimal solutions. If more than one crane in the database has the same configurations, the number of best solutions is multiple according to the number of cranes of same model in the database and the number of crane of that model will be used in the project. For instance, if there are two cranes of the same model in the database and there will be only one crane used in a project, the number of best solutions is two. It is because the model recognises a solution of each crane in the database as a different solution, regardless to the fact that they can be of the same model.

The size of the search space depends on the size of its components, such as the number of possible crane locations, the number of supply points and the number of small group of lifted module(s). The search space of the first scenarios is $4^4.3$ = 768 possible solutions, while that of the scenario 2, 3 and 4 is 243, 512 and 48 respectively. The corresponding ratio between the number of solutions and the search space of the four scenarios 1, 2, 3 and 4 are 0.26%, 0.41%, 0.39%, and 2.08% respectively. The best performance of GA is clearly seen for scenario 4, where the optimal solution is found within about 5 generations only. The good performance of GA model in scenario 1 despite of its small ratio might be explained by the good exploiting feature of GA operators that takes full advantage of location L_3 and GA only finds the best solution by trying different lifted assignment policies. Although scenarios 1 and 3 both have symmetric solutions, GA was harder to find the best solution in scenario 3 rather than in scenario 1 because in scenario 3, the symmetric solutions is not only different in lifted assignment genes but also the crane locations. In such case, GA is expected to work well on both exploitation and exploration to find the best solutions.

5.1.3 Testing the Interaction between the Supply Point Locations and the Crane Locations

The interaction between crane locations and supply point locations was mentioned in Tam et al. (2001) that the change in supply point locations can affect the choice of crane locations and vice versa. In this study, through a number of tests, this interdependent relation has been observed. It can be seen that the changes in crane location layout may result in different supply point layout and different installation sequence. For example, the omission of crane location L_3 in scenario 3 in crane symmetric test series changes not only the crane locations but also the supply point layout and lift sequence as shown in table 5.4.

Table 5.4: The Changes of Supply Points and Lift Sequence in Scenario 1 to Scenario 3 of Symmetric Layout Tests Due to the Change of Tower Crane Layout

Scenario1	S_1	S_2	S_3	S_4	Lift Sequence	Scenario3	S_1	S_2	S_3	S_4	Lift Sequence
Module 1			X		(2)	Module 1		X			(2)
Module 2				X	(4)	Module 2				X	(1)
Module 3	X				(3)	Module 3				X	(4)
Module 4		X			(1)	Module 4				X	(3)
Alternative (symmetric) solution											
Module 1	X				(1)	Module 1	X				(1)
Module 2		X			(4)	Module 2			X		(2)
Module 3				X	(3)	Module 3	X				(4)
Module 4			X		(2)	Module 4	X				(3)

On the other hand, a change in supply point locations may result in a new tower crane layout. For example, in the crane capacity tests, the weight of lifted modules is changed to check the new solution given by GA model. The changed weight of lifted module, eventually causes them to be reallocated in a new supply points, and then, as proven in the scenarios, creates a new tower crane layout. The tower crane location has switched from L_1 in scenario 1 to L_2 in scenario 2 and to L_3 in scenarios 3 and 4. Similarly, the direct changes in supply point layout as in the scenarios of the symmetric tests also result in different crane location layout. The omission of supply point S_4 in scenario 2 and both S_2 & S_4 in scenario 4 eliminated the symmetric solution as in scenario 1 and 3 respectively, resulting in only tower crane layout.

5.1.4 Selection of the Crane Locations

Selecting tower crane locations is among the most important task in site facility layout for high-rise building. Even when there is only one crane and one supply point on site, the tower crane location is not easy to chosen with quantitative reference, especially there are a great number of possible locations. The GA model can be used to choose the tower crane location according to the total hoisting time of all tasks. This application is indeed a small application of the general CLP.

5.1.5 Selection of the Supply Points

If the tower crane location is predetermined, the CLP is simplified as to choose the supply points on site. As discussed in section 7.1.3, the supply point layout also takes an important role in the whole facilities layout since it can affect to the working efficiency of the tower crane. The GA model can be used to select supply points for a fix tower crane layout. This application is also a small application of CLP variety.

5.1.6 Crane Assignment Policy – Balancing the Crane Work

When multiple tower cranes are used, one problem is how to balance crane work such that they can work the most efficiently. A good task assignment to cranes can help to obtain the total small hoisting time, thus reducing the construction time. On the other hand, an inappropriate crane assignment policy (e.g., one crane will lift most of the modules while other cranes are idle) certainly results in a longer total hoisting time. For example, in Fig. 4.3, it can be seen that crane 3 is left idle in batch (k-1) while crane 1 has two tasks. If crane 3 can share the work with crane 1, it definitely reduces the idle time of that crane and the total hoisting time in batch (k-1). The GA model can be used to balance the crane work such that the total hoisting time of them is minimized.

5.1.7 Deciding the Number of Cranes

One of the tasks in crane planning is to decide how many crane are needed for a particular project. For tower crane planning, since the crane's service is within its reach, the number of cranes can be calculated based on the site coverage requirement. Alternatively, the number of cranes also can be reckoned based on the construction completion time. From the distribution of the lifted work during the construction process, the GA model calculate the total hoisting time for a tower crane (or a group of tower cranes) and the total hoisting time, in turn, to be the criterion to determine the number of cranes. If the user cannot decide how many cranes will be used, the program will take the number of crane available in the database as the default value for its course.

The following number-of-crane tests aim to check if the model chooses a good number of cranes for different projects. Two small examples are taken with different scenarios to test the GA results. The examples are designed in order to particularly highlight the cases where the program should use more than one crane and the cases where only one crane is preferable. In each example, the tests are conducted with 3 options (N_{crane} = 1, 2 and 3), one after another.

In the small examples, there are 3 possible crane locations, 4 lifted modules and 2 supply points. Crane locations and demand points share the same vertical line of symmetry. There are only 3 cranes available in the database. The tower crane layout is illustrated as in Fig. 5.19 (next page).

To impose the suitable number of cranes, we control by the priority matrix. Two scenarios are presented, the first one with the priority matrix of 1-1-1-1 for 4 lifted modules, meaning that the 4 jobs are independent and can be installed in the same batch and the second scenario is with the priority matrix of 3-3-2-1, meaning that the 4^{th} module has to be installed first, then the 3^{rd} one, and lastly the 1^{st} and 2^{nd} can be install at the same time. The former creates good conditions to use more cranes to achieve the shorter hoisting time while the latter scenario would prefer less number of cranes since it is no use to more cranes and let them idle. Using multiple cranes in this case may result in a total longer hoisting time. The results are tabulated in the table 5.5.

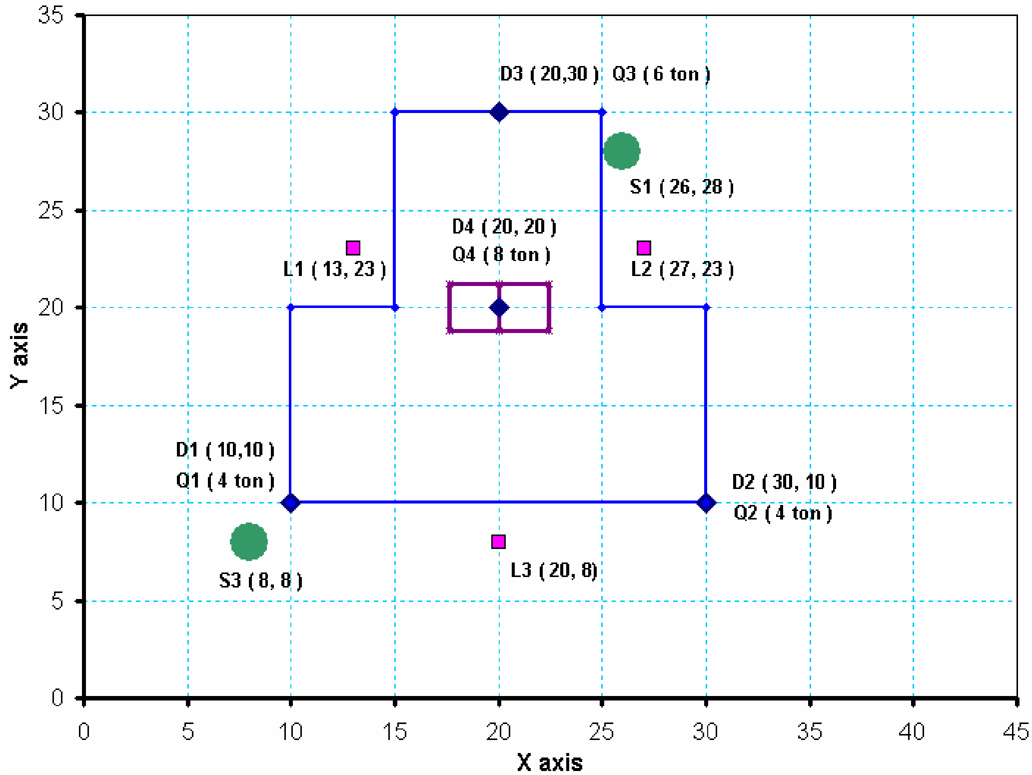


Figure 5.19: Tower Crane Layout – the Number-of-Crane Tests

Table 5.5: Results of the Number-of-Crane Tests

1st scenario	Test's number										Best
1-1-1-1	1	2	3	4	5	6	7	8	9	10	Fitness
1 crane	+	+	+	+	+	-	-	-	+	+	1.34096
2 cranes	-	+	+	-	-	+	-	+	+	+	1.16322
3 cranes	+	+	+	-	+	+	+	+	+	+	0.992595
2nd scenario 3-3-2-1	1	2	3	4	5	6	7	8	9	10	Best Fitness
1 crane	+	-	+	+	+	+	+	+	+	+	1.34096
2 cranes	+	-	+	+	-	-	+	+	+	-	1.34096 *
3 cranes	+	-	-	-	-	-	+	-	-	-	1.34096 *

(*) The number of crane is automatically reduced to 1.

(+) GA model is successful to find optimum in 50 generations.

(-) The optimum solution has not yet been found after 50 generations.

It can be seen that, generally, with the more number of crane provided, the worse GA performs. There seems to have an exception in the 1st scenario when N_{crane} = 3 has very good chance of success, this phenomenon once again, can be explained by the high ratio of the number of the optimal solutions and the size of the search space. It should be noted that, to simplify the situation, the crane configurations for every crane in library are the same, thus the number of the optimal solutions in this scenario is $(3*2*1)*(3*2*1)*(4^3) = 2304$. The size of the search space is $(3*2*1)*(4^2)*(4^3)*(3*2*1) = 36864$ solutions. The ratio of the number of the optimal solution and the size of the search space is 1/16 (very high). In scenario 1 with $N_{crane} = 2$, the number of optimal solutions is $3*(3*2*1)*(4^2) = 288$ while the search space is $(3*2)*(4^2)*(4^2)*(3.2) = 9126$ solutions. The ratio of the number of the optimal solution and the size of the search space is 1/31.6875. Thus, even with the larger search space and number of cranes, GA performance with $N_{crane} = 3$ in scenario 1 is better.

5.1.8 Refinement of the Lift Sequence – Crane Scheduling

The installation order of lifted modules may change due to practical constraints or construction techniques. The model also can be used to test the proposed lifted sequence if it is better in terms of total hoisting time and other related criteria such as crane collision possibility. The refinement of lifted sequence directly leads to a practical tower crane(s) scheduling.

5.1.9 Pre-caster Deliverer Plan

Since the GA model can determine the delivery point for each lifted task, it may be of usefulness to utilize those results in planning for pre-caster schedule. Base on the number of lifted module at each supply point, as well as their installation schedule it is possible to issue a suitable delivering plan for pre-casters or for auxiliary equipment to deliver precast units from temporary storages.

5.1.10 Further Development - Checking the Supply Point Capacity

If the supply point capacity is taken into account, the GA model can be used to check the sufficient capacity of each supply point to ensure that it can store all the assigned lifted units (for a period of time) or large enough for the site operations such as concreting or steel work. This application gives a more realistic assignment plan for different supply points on site.

5.2 Practical Application – A Case Study in PUNNGOL Site

Case studies have been carried out to test the GA model for practical projects. Those case studies are aimed to test the model in large-scale projects. The GA model has been employed to design tower crane layout in a project of Poh Lian Construction Pte. Ltd. in Punggol site. The project information is tabulated in table 5.6.

5.2.1 Project Information

Table 5.6: Summary of Project Information

Name	Punggol East Contract 31
Developer	Housing and Development Board (HDB)
Contractor	Poh Lian Construction Pte Ltd, a wholly-owned subsidiary of UFS.
Expected year of completion	2006
Estimated Contract Value	S$87.7 million

The Project consists of 10 blocks of flats with 582 dwelling units and a basement car park. The 10 block of high-rise precast buildings are symmetric, so it is possible to consider half of the project. The left side of the project consisting of block 635A-635B-635C and 636A-636B is chosen. The crane work of the basement car park is not considered.

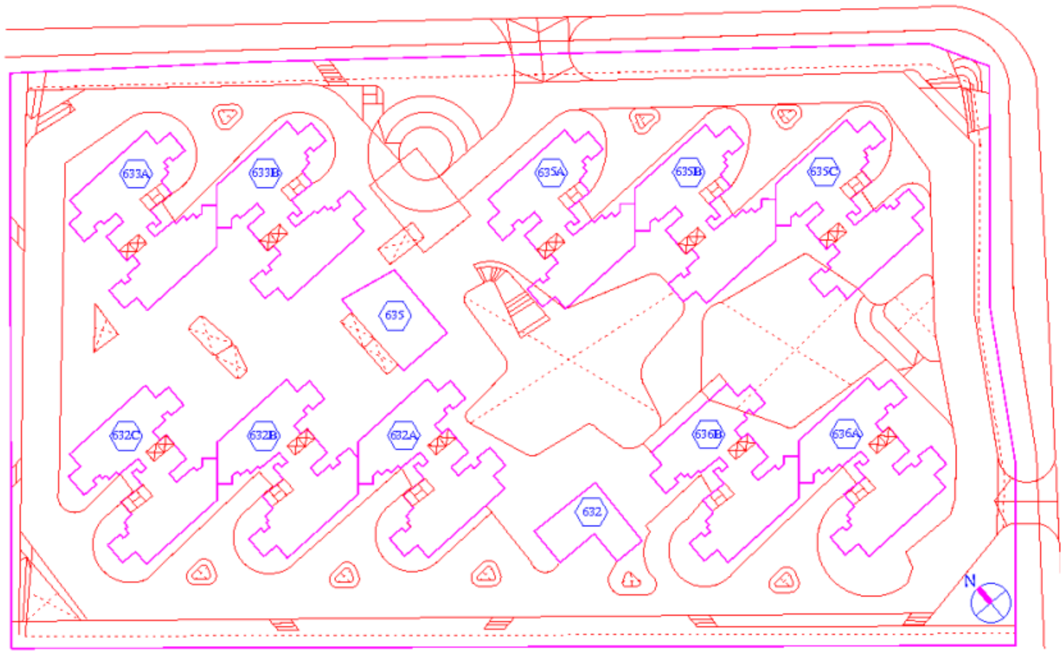


Figure 5.20: Total PUNGGOL Site Layout – Poh Lian Project

Based on the foundations of the building footprint and the site constraints, the possible tower crane locations are proposed. It is noted that, due to the presence of the LRT line along the North side of the site, crane location are restricted to this area according to Singapore regulations. Also, considering the external access and site constraints, the possible supply points are predetermined.

The company has 6 models of Comansa tower cranes of 2 Linden LC-2070 and 4 Linden LC-2074. A picture of a tower crane Linden LC-2074 is presented beside.

Figure 5.21: Tower Crane LC-2074

The configurations of these cranes are attached in appendix B. Based on the coverage requirements of the site, it is determined that there will be two tower cranes to serve the three blocks 635A- 635B- 635C and there will be only one tower crane to serve block 636A and 636B. Therefore, the two groups of buildings are treated separately as illustrated below.

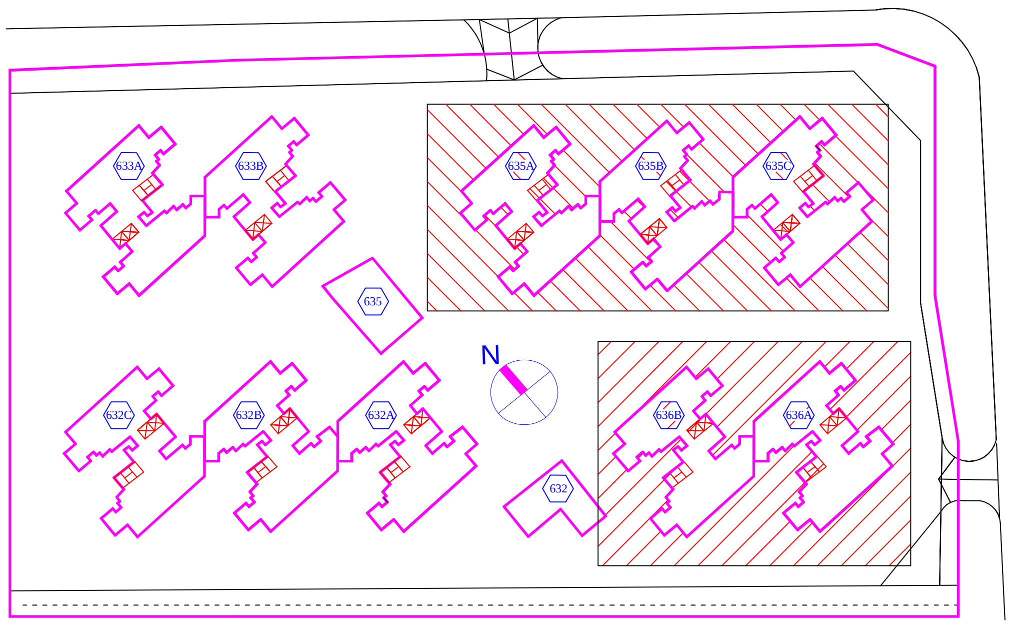


Figure 5.22: Key Plan of Two Groups of Blocks 635A-635B-635C and 636A-636B

5.2.2 Implementation of the GA Model - Data Preparations

To find out the possible crane locations, considerations are made taking into account the restriction of building foundations, restriction of the site, coverage requirements (of the LC-2074 with 40-meter boom), and dismantling procedures. It is also noted that the final standing height of the tower crane is 74.1 meters so there is necessary to tie its mast to the building. The proposed crane possible locations are chosen such that they are near the main vertical structures that can provide enough strength for those connections.

5.2.2.1 Block 636A & 636B – Single Tower Crane

There are total of 5 possible locations for tower crane locations as in table 5.7.

Table 5.7: Possible Tower Crane Locations – Block 636A & 636B – PUNGGOL Site

Name	Co-ordinates			Note
	X	Y	Z	
L1	13.0	14.8	66.0	In middle of the site, making use of other tower cranes in assembling and dismantling procedures.
L2	16.80	6.3	66.0	
L3	21.50	14.8	66.0	
L4	37.00	29.6	74.1	Near the south boundary of the site with access, using mobile cranes to assemble and dismantle.
L5	32.70	38.0	74.1	

The possible supply/delivery points for the crane are determined based on the availability of access roads, site constraints (space availability) and the coverage area of the 40-meter boom tower crane (Linden LC-2074). There are three possible supply point locations for the two block 636 A & B as tabulated in table 5.8.

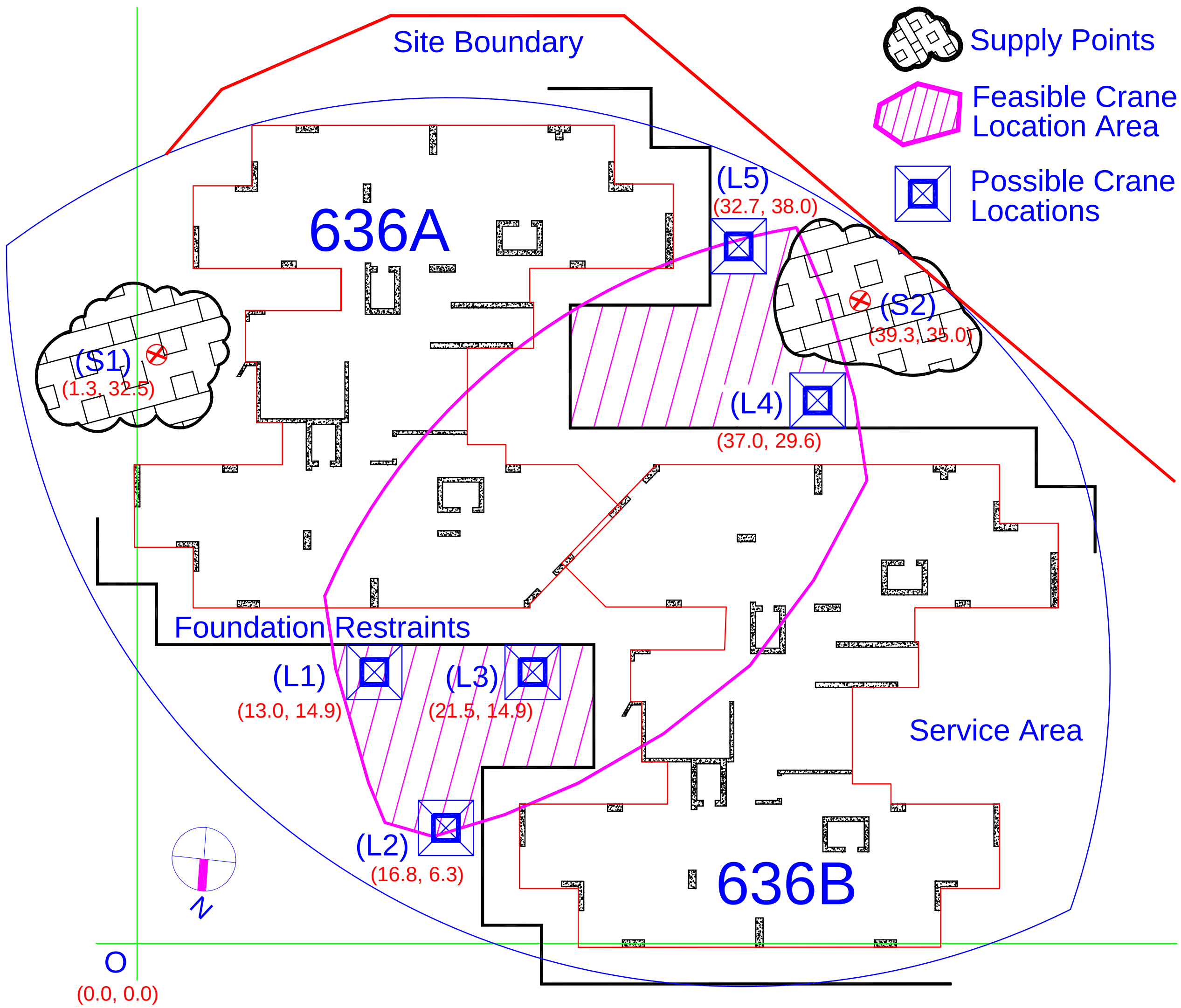
Table 5.8: Possible Supply Point Locations – Block 636A & 636B – PUNGGOL Site

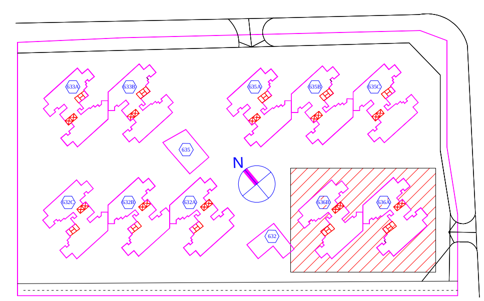
Name	Co-ordinates			Note
	X	Y	Z	
S1	1.3	32.5	1.0	Near road access, on the way to internal transportation paths.
S2	39.3	35.0	1.0	Near road access, separate from the internal transportation path on site.
S3	48.8	12.5	1.0	Internal site position, dependent on the internal transportation on site

The precast components, their weights and locations are calculated from detailed drawings. They are grouped in small groups based on the geometric of the building, type of elements and installation order. Details of name, coordinates, weight, group and installation priority of all precast units can be found in section B.5.

The site layout is illustrated as in Fig. 5.19.

Figure 5.23: Site Layout of Block 636A & 636B – PUNGGOL Site





Key plan

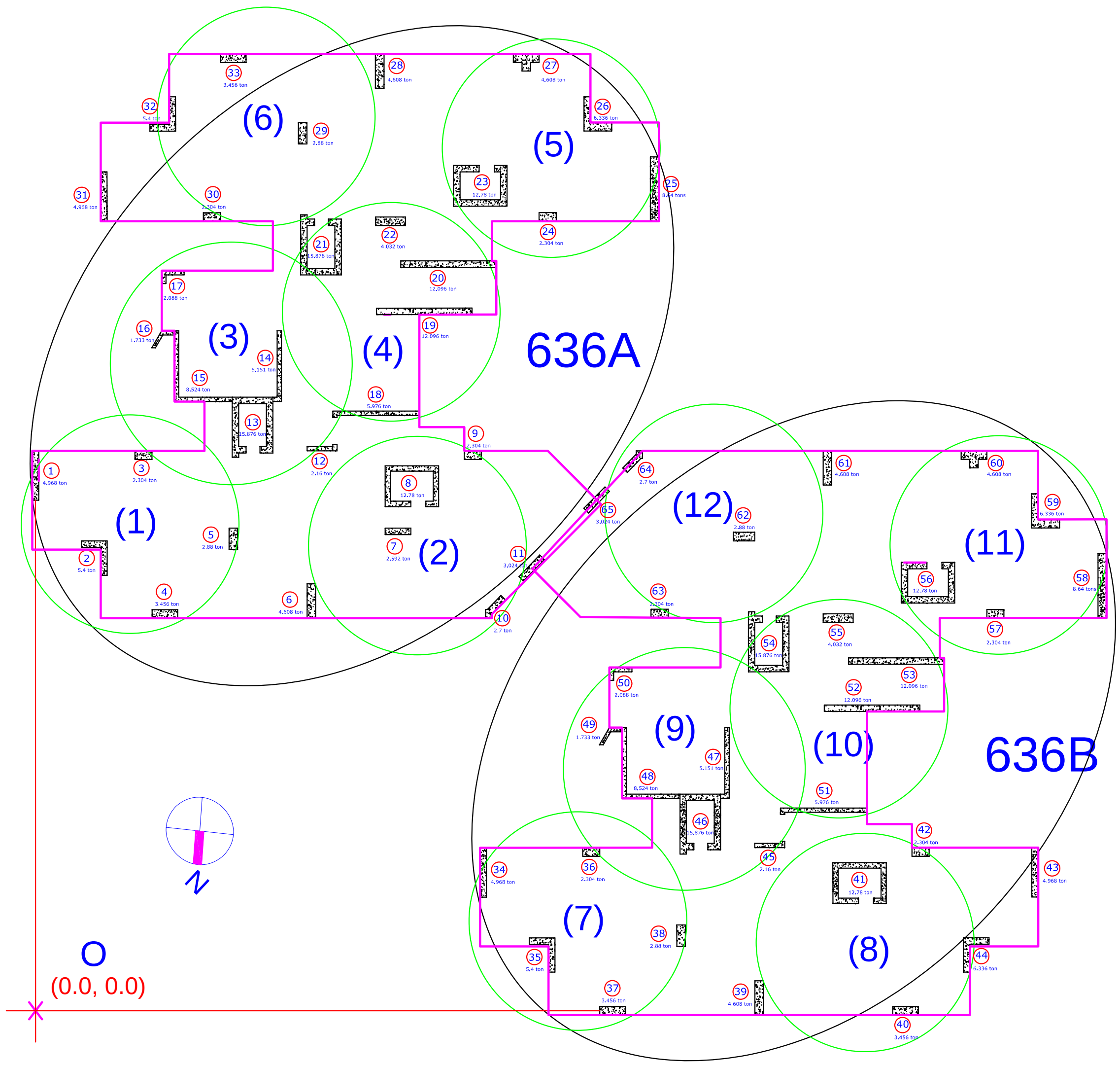
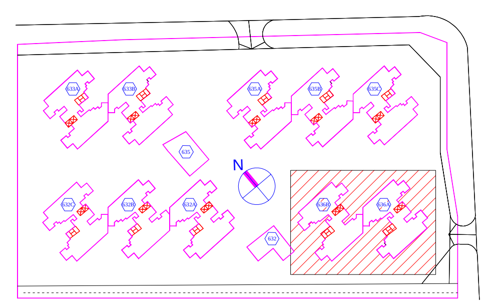


Figure 5.24: Layout of Vertical Members (Precast Columns, Walls, Chutes and Core Lifts) of Block 636A & 636B – PUNGGOL Site

The precast elements are grouped according to their geometrical locations.



Key plan

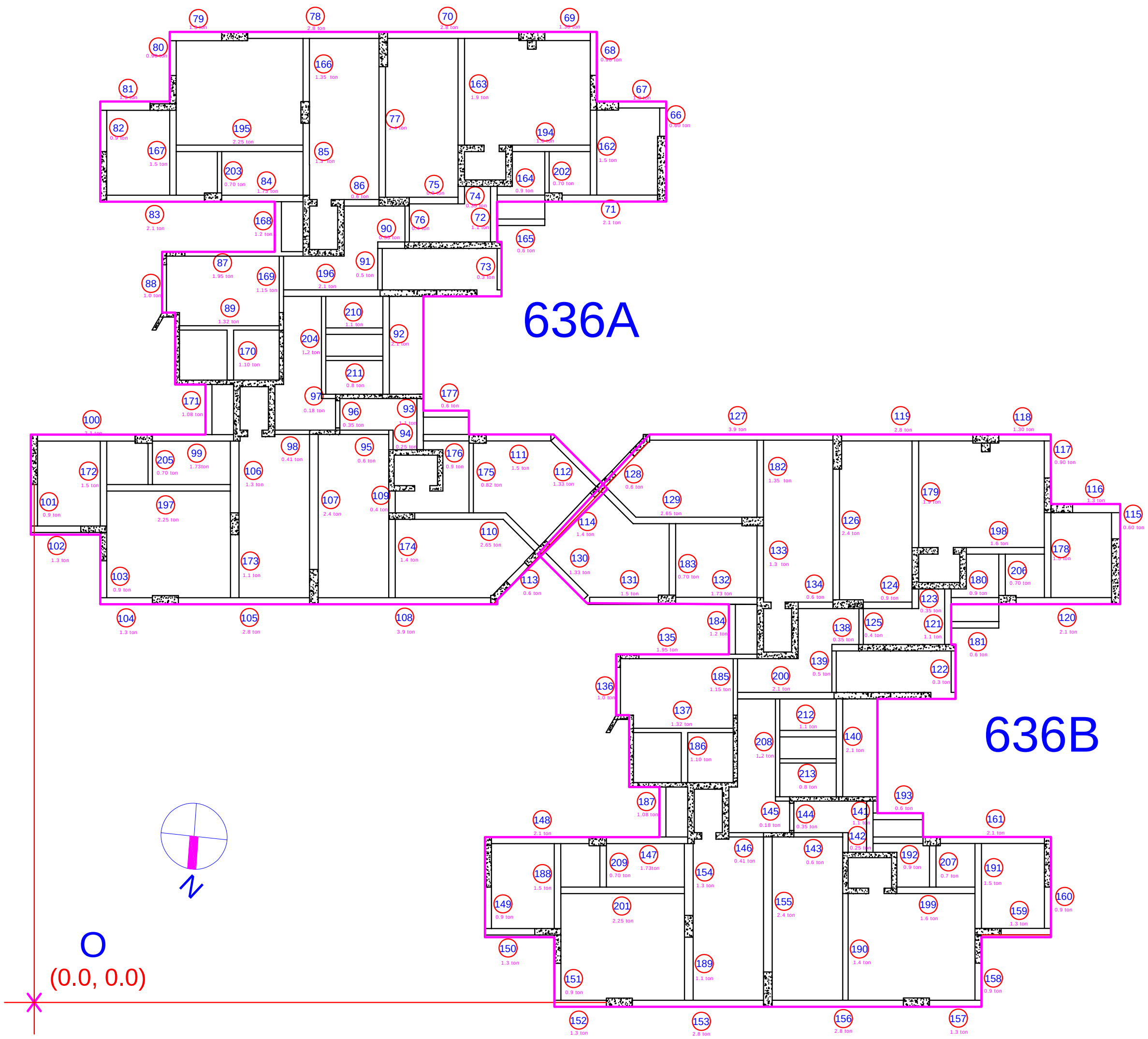
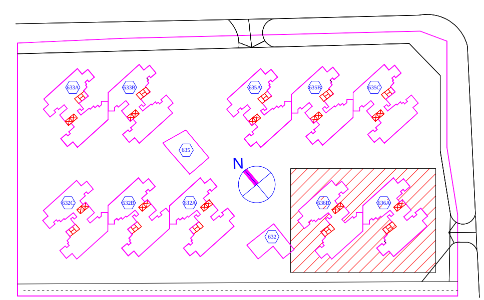


Figure 5.25: Layout of Horizontal Members (Precast Beams) of Block 636A & 636B – PUNGGOL Site

The precast beams are grouped according to their geometrical locations and installation order.



Key plan

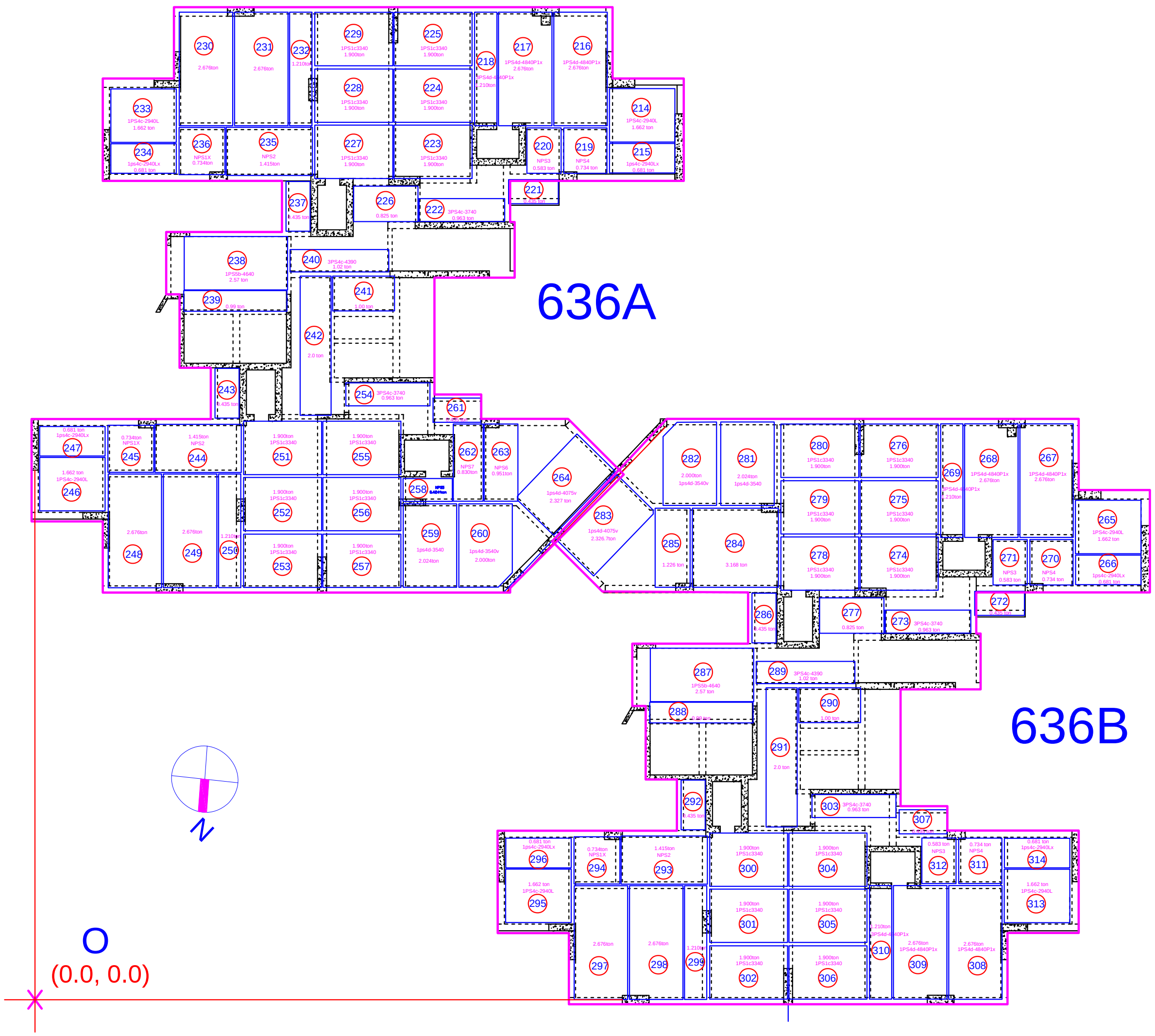
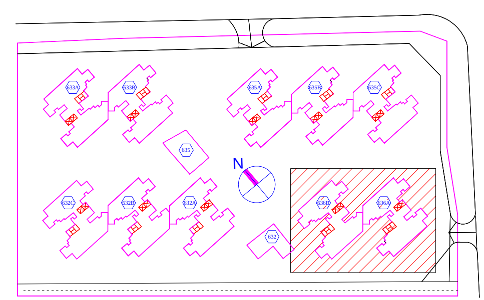


Figure 5.26: Layout of Horizontal Members (Precast Flanks) of Block 636A & 636B – PUNGGOL Site

The precast flanks are grouped according to their geometrical locations.



Key plan

5.2.2.2 Block 635A, 635B & 635C – Multiple Tower Cranes

There are total of 13 possible locations for tower crane locations as in table 5.7. These locations are in four groups in the areas between the three blocks. Since the number of blocks is three while the number of cranes is two, at least one crane will work in two blocks, or the middle block will be served by both cranes. This feature of the project will affect on the task grouping to define the working zone of each crane.

Table 5.9: Possible Tower Crane Locations – Block 635A, B & C – PUNGGOL Site

Name	Co-ordinates			Note
	X	Y	Z	
L6	-4.1	-1.5	66.0	Group 1: In middle of the site, making use of other tower cranes in assembling and dismantling procedures.
L7	0.7	-1.5	66.0	
L8	-4.1	-5.1	66.0	
L9	-6.0	-20.0	74.1	Group 2: Near the south boundary of the site with access, using mobile cranes to assemble and dismantle.
L10	-10.8	-20	74.1	
L11	-6.0	-23.6	74.1	
L12	7.0	-38.5	74.1	Group 3: Near the south boundary of the site with access, using mobile cranes to assemble and dismantle.
L13	12.7	-38.5	74.1	
L14	15.0	-42.2	74.1	
L15	23.2	-16.7	74.1 (*)	Group 4: In middle of the site, making use of other tower cranes or using mobile cranes (from internal positions) in assembling and dismantling procedures. (*) If using another tower crane to help dismantling/assembling this tower crane in these locations, the height of the crane is 66.0 meters.
L16	17.0	-20.0	74.1 (*)	
L17	24.5	-23.6	74.1 (*)	
L18	27.7	-23.6	74.1 (*)	

It should be noted that if the crane locations in group 2 and 3 are in the North side of the site, where there presents the LRT line nearby. Thus, if those locations are chosen, further considerations should be made to conform to the Singapore building regulations concerning the safety aspect.

The possible supply/delivery points for the crane are determined based on the availability of access roads, site constraints (space availability) and the coverage area of the 40-meter boom tower crane (Linden LC-2074). There are five possible supply point locations for the two block 635 A, B & C as tabulated in table 5.10.

Table 5.10: Possible Supply Point Locations – Block 636A, B & C – PUNGGOL Site

Name	Co-ordinates			Note
	X	Y	Z	
S4	-16.7	16.6	1.0	Near road access, separate from the internal transportation path on site
S5	-17.5	-24.3	1.0	Near road access, separate from the internal transportation path on site
S6	2.1	-39.7	1.0	Near road access, separate from the internal transportation path on site
S7	30.0	-18.8	1.0	Internal site position, dependent on the internal transportation on site
S8	44.7	-44.1	1.0	Internal site position, near road access to internal transportation paths

The precast components, their weights and locations are calculated from detailed drawings. They are grouped in small groups based on the geometric of the building, type of elements and installation order. Details of name, coordinates, weight, group and installation priority of all precast units can be found in section B.5.

The site layout is illustrated as in Fig. 5.27.

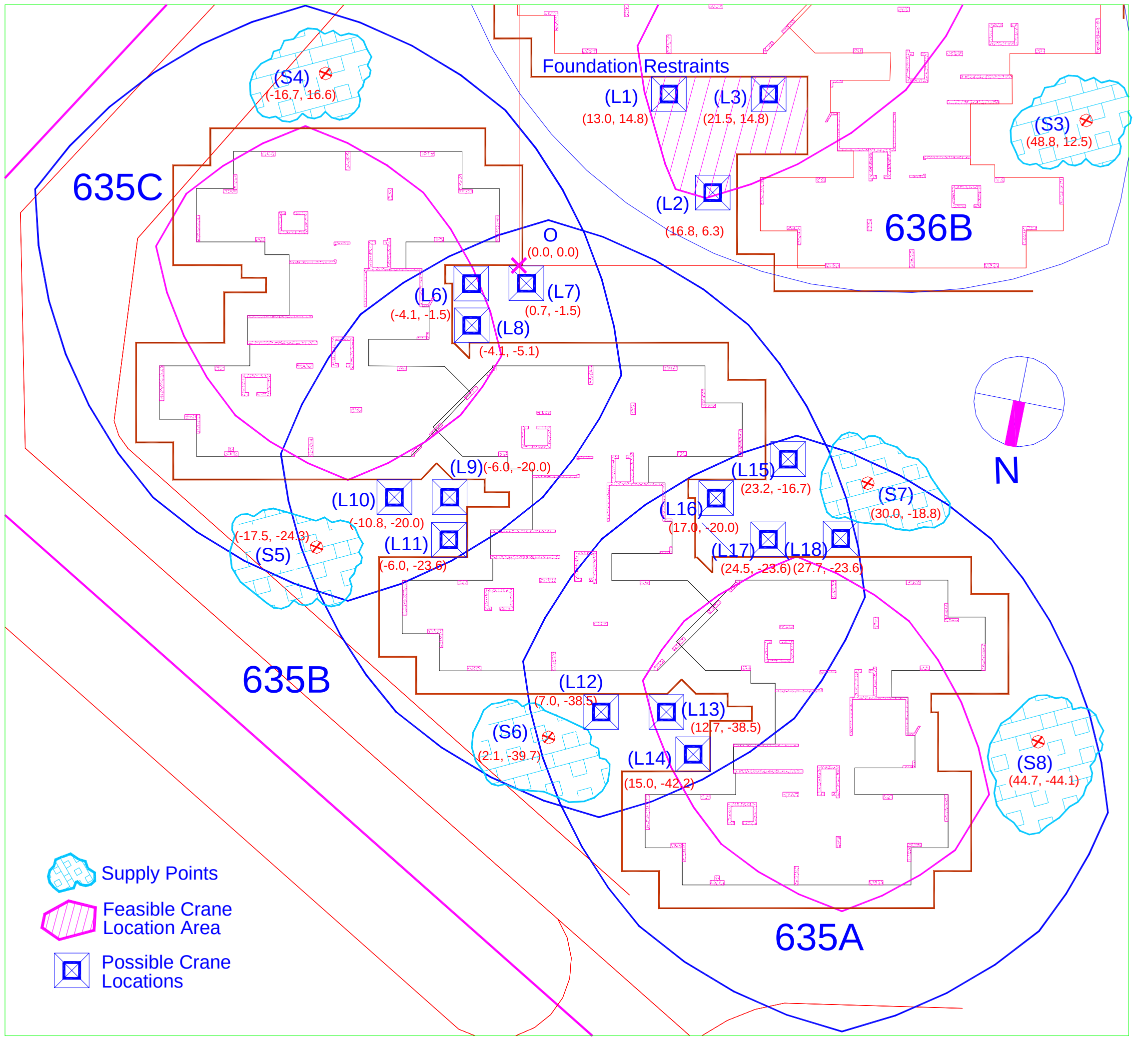
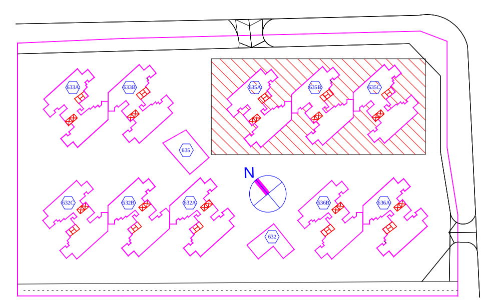


Figure 5.27: Site Layout of Block 635A, 635B & 635C – PUNGGOL Site



Key plan

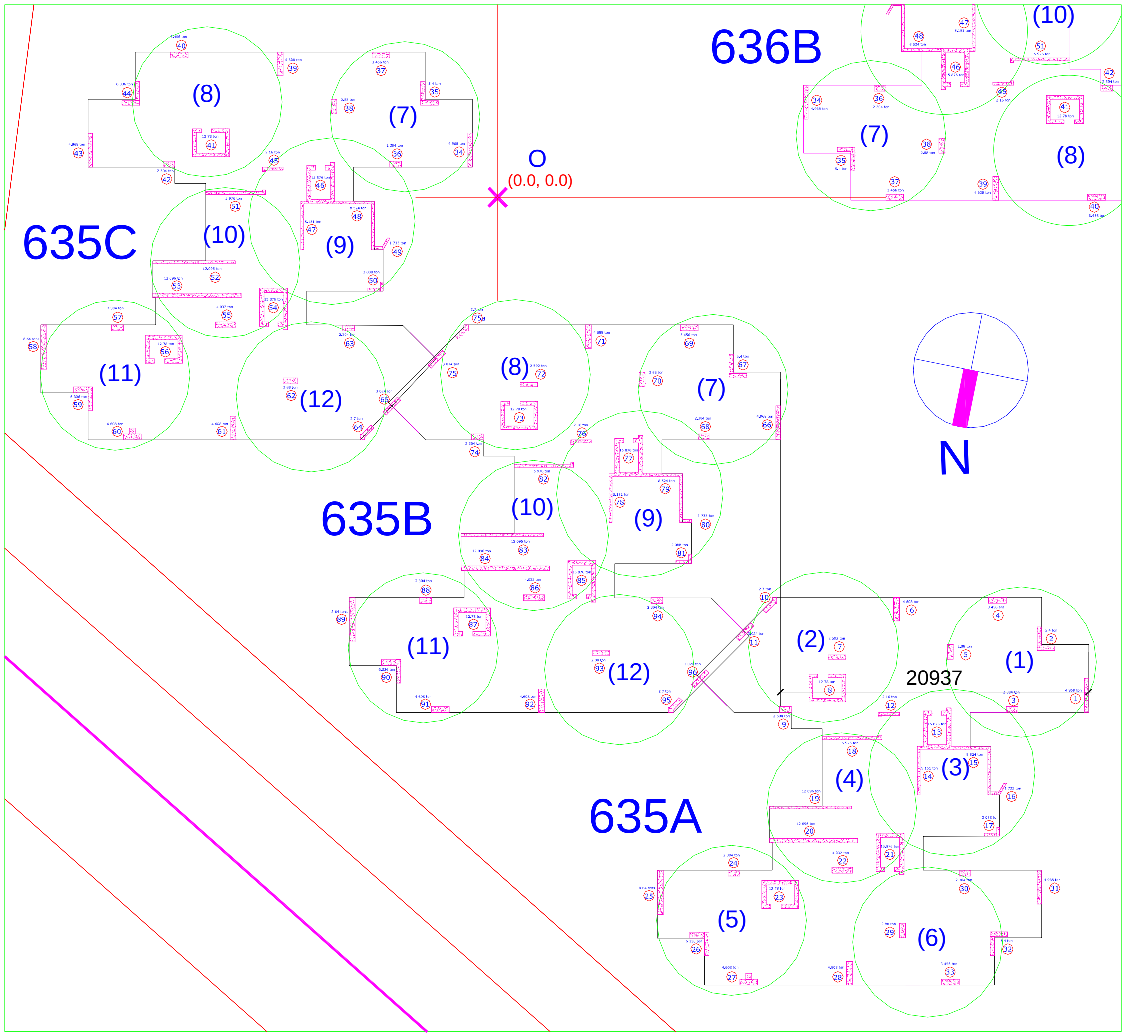
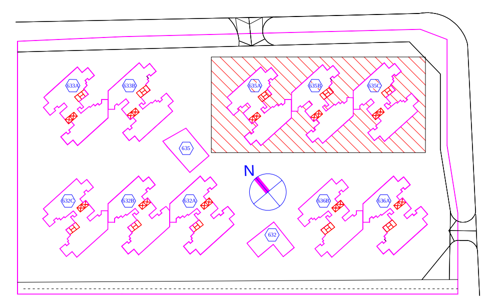


Figure 5.28: Layout of Vertical Members (Precast Columns, Walls, Chutes and Core Lifts) of Block 635A , 635B & 635C – PUNGGOL Site

The precast elements are grouped according to their geometrical locations.



Key plan

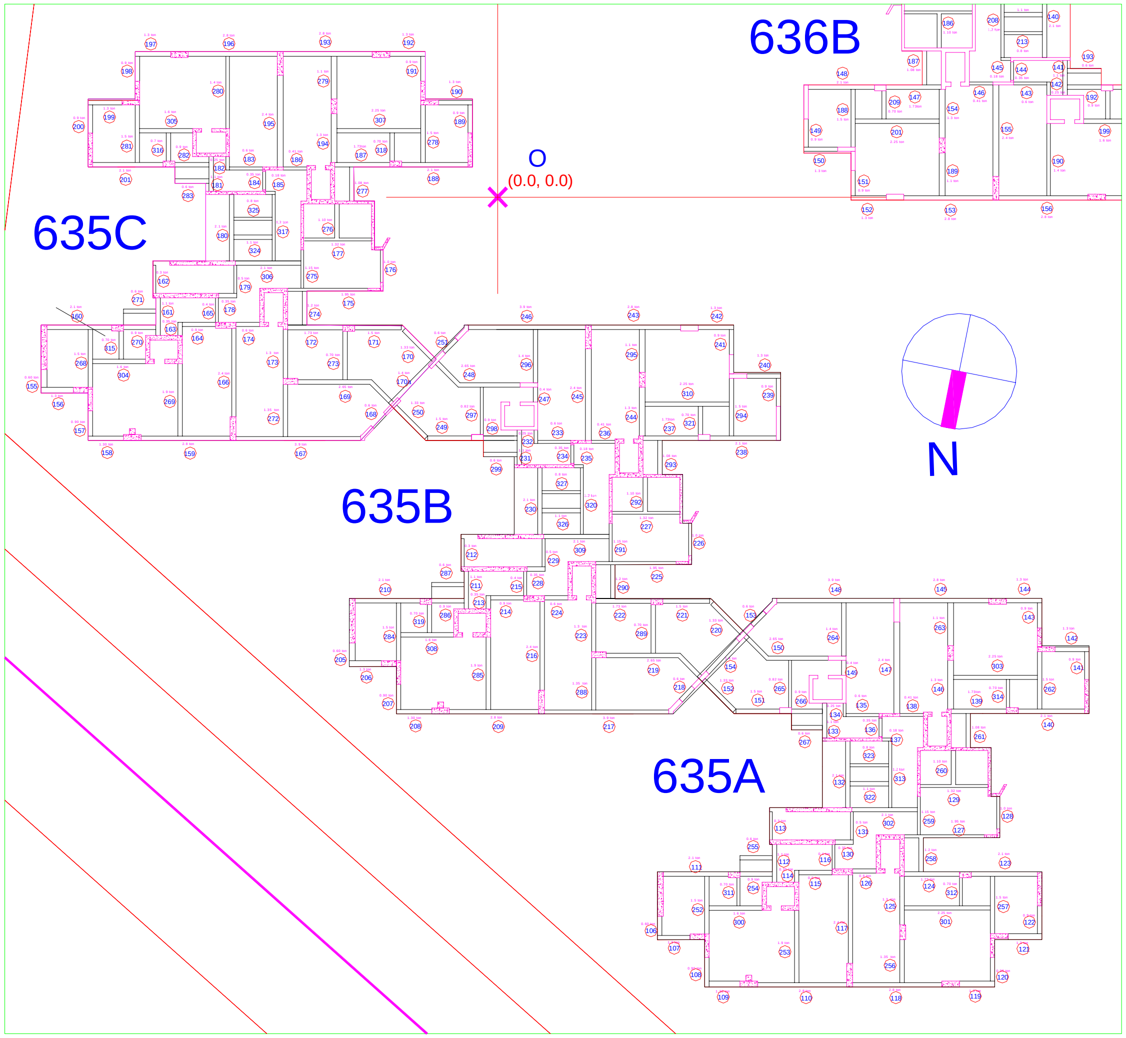
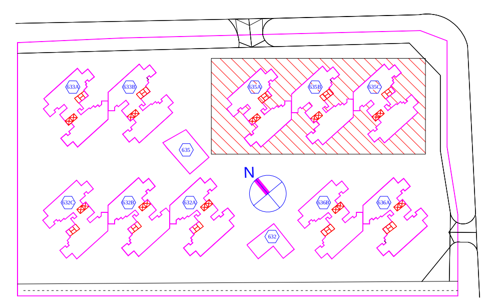


Figure 5.29: Layout of Horizontal Members (Precast Beams) of Block 635A, 635B & 635C – PUNGGOL Site

The precast beams are grouped according to their blocks and installation order.



Key plan

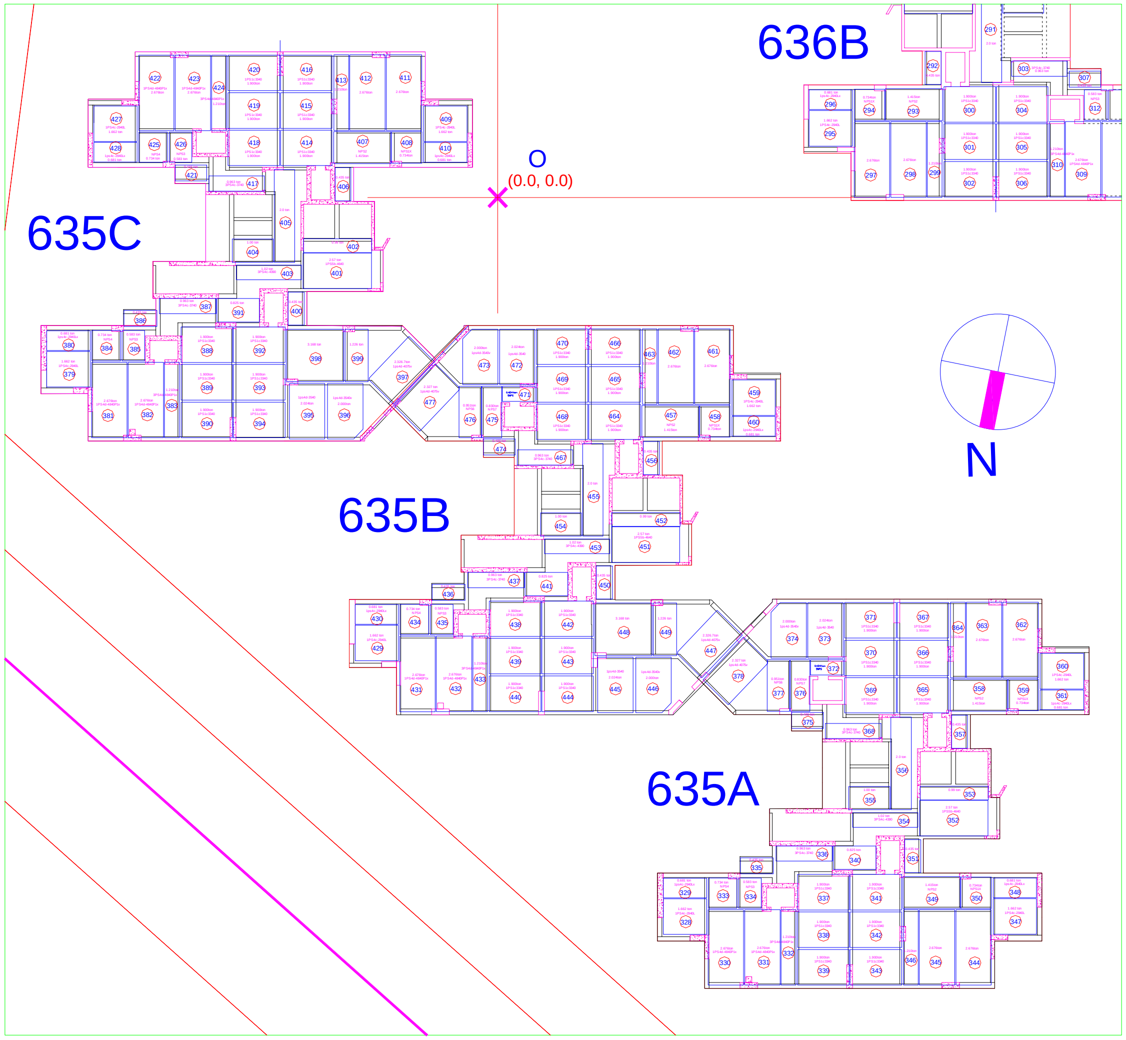
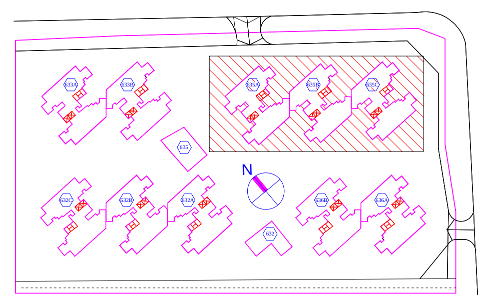


Figure 5.30: Layout of Horizontal Members (Precast Flanks) of Block 635A , 635B & 635C – PUNGGOL Site

The precast flanks are grouped according to their block.



Key plan

5.2.3 Results

The plan layout of the building is the same for every floor, and the lift cycle is repeated for every two floors. Therefore, without the loss of generality, the tower crane lay out can be decided by using the GA model for only one cycle of installation (one batch for vertical members and two floors for horizontal members). The CLP in Block 636A & B is implemented in two scenarios, (1) for the 2 and 3 floors and (2) for the 13 and 14th floors to see the effect of building height to the site facility layout. Each scenario applied the GA model in four different runs to test the consistency and convergence of the results. The results are summarised below.

5.2.3.1 Block 636A & 636B – Single Tower Crane

In both scenarios, the tower crane location L_2 governed. The Linden LC-2074 has enough capacity to serve all the lifted tasks during installations. The lifted assignments of lifted group to supply point are tabulated as in table 5.9.

Table 5.11: Lifted Assignments of Groups of Precast Components to Supply Points

Group Name	Supply point chosen	Group Name	Supply point chosen	Group Name	Supply point chosen
1	S_1	13	S_1	25	S_2
2	S_1	14	S_2	26	S_2
3	S_1	15	S_2	27	S_2
4	S_2	16	S_1	28	S_1
5	S_2	17	S_1	29	S_2
6	S_2	18	S_2	30	S_2
7	S_1	19	S_2	31	S_1
8	S_1	20	S_1	32	S_1
9	S_1	21	S_2	33	S_2
10	S_2	22	S_1	34	S_2
11	S_2	23	S_1		
12	S_2	24	S_1		

GA tests are conducted with P_x = 0.9, P_{mut} = 0.1, $P_{replace}$ = 0.25, N_{pop} = 70 and $N^{total}_{generations}$ = 10000 (only first 1000 generation is shown in Fig. 5.27 and 5.28). The total hoisting times are 488.5 and 1078.4 minutes in scenarios (1) and (2) respectively. The difference between the two results shows that the vertical hook movements takes an importance part in high-rise buildings.

It is also found that there is no change in the site layout (i.e. the change in the optimal location of tower crane and/or supply points) in the two scenarios. It is because the plan layout of the building is the same for every floor and the hook movements between vertical and horizontal directions are assumed to be consecutive. Therefore, the site facilities should not change as the building gets higher.

The GA performances of the two scenarios are illustrated in Fig. 5.31 and 5.32.

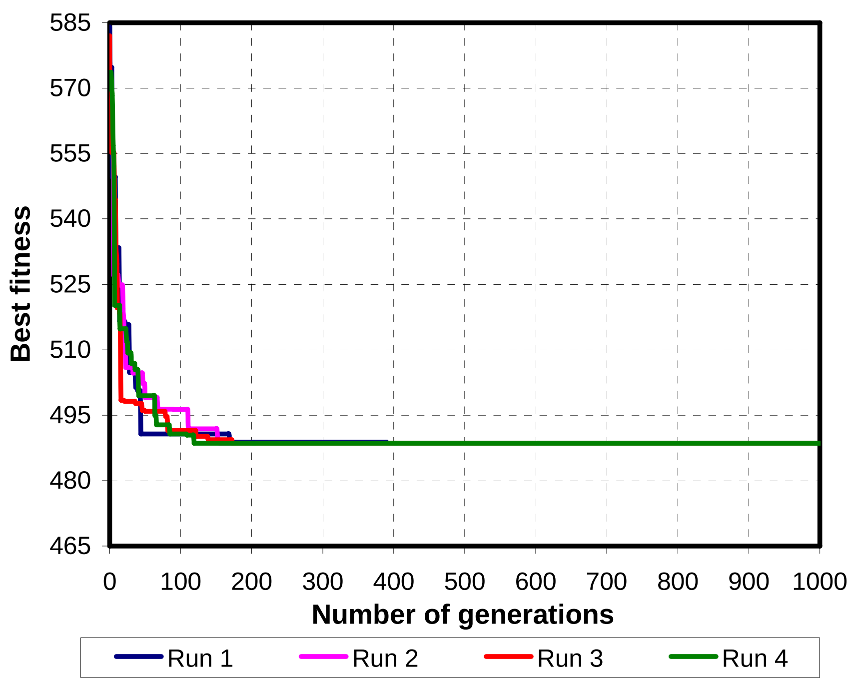


Figure 5.31: GA Performance of 4 Independent Runs in Scenario 1 – The First Typical Cycle of Installation (2nd and 3rd Floors) - Block 636A&B - PUNGGOL Site

The difference between the best of 70 random solutions in the initial population and the optimal is (580-488.5)*100%/488.5 = 18.73 % while the difference between the mean fitness value of the first population and the optimal one is about (780-488.5)*100%/488.5 = 59.67%. Those numbers show how effective the GA model can save for the hoisting time of tower crane.

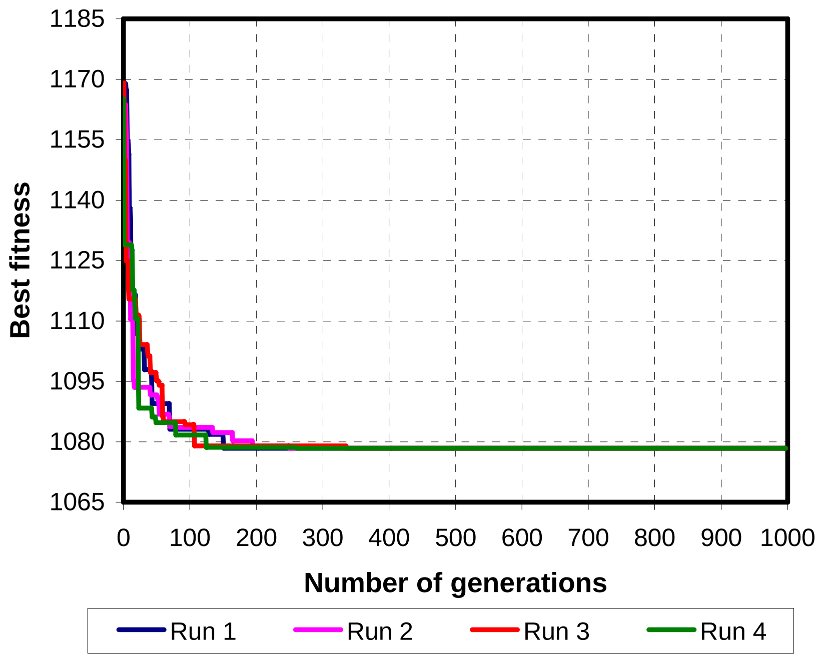


Figure 5.32: GA Performance of 4 Independent Runs in Scenario 2 – The Last Cycle of Installation (13th and 14th Floors) - Block 636A&B - PUNGGOL Site

In this scenarios, the difference between the best of 70 random solutions in the initial population and the optimal is (1165-1078.4)*100%/1078.4 = 8.03 % while the difference between the mean fitness value of the first population and the optimal one is about (1350-1078.4)*100%/1078.4 = 25.18%. This numbers are smaller as compared to the previous scenario because for the last installation cycle (13th and 14th floor) the hoisting time of vertical movement contributes more than 50% of the total hoisting time while the GA model is to optimize the horizontal movement only.

5.2.3.2 Block 635A&B&C – Multiple Tower Cranes

The multiple tower crane tests are applied for block 635A, B & C in Punggol site. The total hoisting time is calculated for the installation of the structural precast components of the second floor only. Total structural precast components are grouped in 12 groups according to blocks. The first three groups are the total vertical structures including columns, shear walls, lift cores, and refuse chutes of the three blocks. These groups are in the first batch and have the first lifting order (priority 1). The next batch consists of the three groups of primary beams with priority 2. Then, the third batch with secondary beams with priority 3. The last batch (priority 4) includes the three groups of precast flanks of the three blocks.

GA tests are conducted with P_x = 0.9, P_{mut} = 0.1, $P_{replace}$ = 0.25, N_{pop} = 28 and $N^{total}_{generations}$ = 10000 (only first 400 generation is shown in Fig. 5.30).

The two locations L_7 and L_{15} are chosen while the actual locations on site are L_7 and L_{12}. Two tower cranes Linden LC-2074 are chosen from the crane library. The lifted assignments of lifted group to supply point, to crane and the tower crane chosen from the database are tabulated as in table 5.10.

Table 5.12: Assignment Policies for Groups of Precast Components - Optimised Solution

Group Name	Supply point chosen	Group Name	Assign Job to Tower Crane	Group Name	Tower Crane chosen
1	4th (S_7)	1	2nd (L_{15})	1	5th (T_5)
2	2nd (S_5)	2	1st (L_7)	2	2nd (T_2)
3	2nd (S_5)	3	1st (L_7)	3	2nd (T_2)
4	4th (S_7)	4	2nd (L_{15})	4	5th (T_5)
5	2nd (S_5)	5	1st (L_7)	5	2nd (T_2)
6	3rd (S_6)	6	1st (L_7)	6	2nd (T_2)
7	5th (S_8)	7	2nd (L_{15})	7	5th (T_5)
8	2nd (S_5)	8	1st (L_7)	8	2nd (T_2)
9	3rd (S_6)	9	1st (L_7)	9	2nd (T_2)
10	5th (S_8)	10	2nd (L_{15})	10	5th (T_5)
11	2nd (S_5)	11	1st (L_7)	11	2nd (T_2)
12	3rd (S_6)	12	1st (L_7)	12	2nd (T_2)

The optimal total hoisting time is 336.252 minutes. The optimised tower crane layout for both of the two groups of blocks is illustrated in figure 5.33.

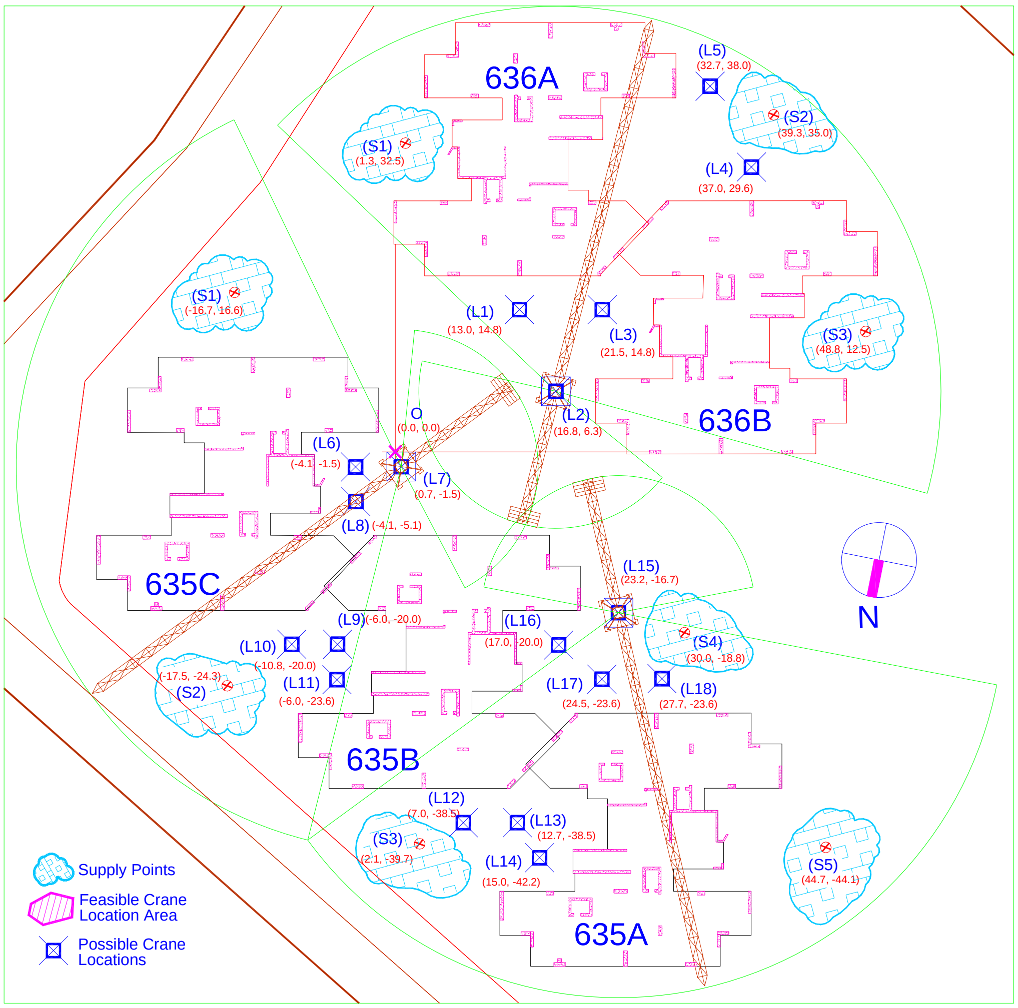


Figure 5.33: Optimised Tower Crane Layout of PUNGGOL Site

The assembling of the group of tower cranes is described below. First, a 400-ton mobile crane helps to assembly the tower crane at L_{15} at the middle of the site. This tower crane is the used to assembly the other tower cranes at location L_2 and L_7. The dismantling procedure is inverse order. Tower crane at L_{15} dismantles the other two tower cranes first. Lastly, the mobile crane helps to dismantle this tower crane.

Since this solution is different from the actual tower crane layout chosen on site. Further test is conducted to compare the efficiency of the GA model versus the actual solution on site. The optimised tower crane layout generated by the GA model is similar to the proposed tower crane layout in real site practice. Two out of three tower crane locations are the same (L_2 and L_7). The third tower crane location in the optimised solution is at location L_{15} while that of the actual site solution is at location L_{12}. The GA model is used to check the actual solution on site proposed by the site engineer. The result of this test is presented below.

The actual locations chosen on site are L_7 and L_{12}. GA model tries to optimise the tower crane supply points and assignment policies only. Two tower cranes Linden LC-2074 are chosen from the crane library. Since the tower crane locations is changed, the supply points and the crane assignment are also changed. The lifted assignments of lifted group to supply point, to crane and the tower crane chosen from the database are tabulated as in table 5.11.

Table 5.13: Assignment Policies for Groups of Precast Components – On Site Solution

Group Name	Supply point chosen	Group Name	Assign Job to Tower Crane	Group Name	Tower Crane chosen
1	4^{th} (S_7)	1	2^{nd} (L_{12})	1	2^{nd} (T_2)
2	1^{st} (S_4)	2	1^{st} (L_7)	2	1^{st} (T_1)
3	2^{nd} (S_5)	3	1^{st} (L_7)	3	1^{st} (T_1)
4	4^{th} (S_7)	4	2^{nd} (L_{12})	4	2^{nd} (T_2)
5	1^{st} (S_4)	5	1^{st} (L_7)	5	1^{st} (T_1)
6	4^{th} (S_7)	6	1^{st} (L_7)	6	1^{st} (T_1)
7	5^{th} (S_8)	7	2^{nd} (L_{12})	7	2^{nd} (T_2)
8	2^{nd} (S_5)	8	1^{st} (L_7)	8	1^{st} (T_1)
9	2^{nd} (S_5)	9	1^{st} (L_7)	9	1^{st} (T_1)
10	5^{th} (S_8)	10	2^{nd} (L_{12})	10	2^{nd} (T_2)
11	2^{nd} (S_5)	11	1^{st} (L_7)	11	1^{st} (T_1)
12	2^{nd} (S_5)	12	2^{nd} (L_{12})	12	2^{nd} (T_2)

The location L_{12} is at the North side of the site, where presents the LRT line. Thus, precautions have been made to ensure the installation and operations of the tower crane are safe. The tower crane is tied into the building for its stability. The actual tower crane layout on site is illustrated in Fig. 5.34.

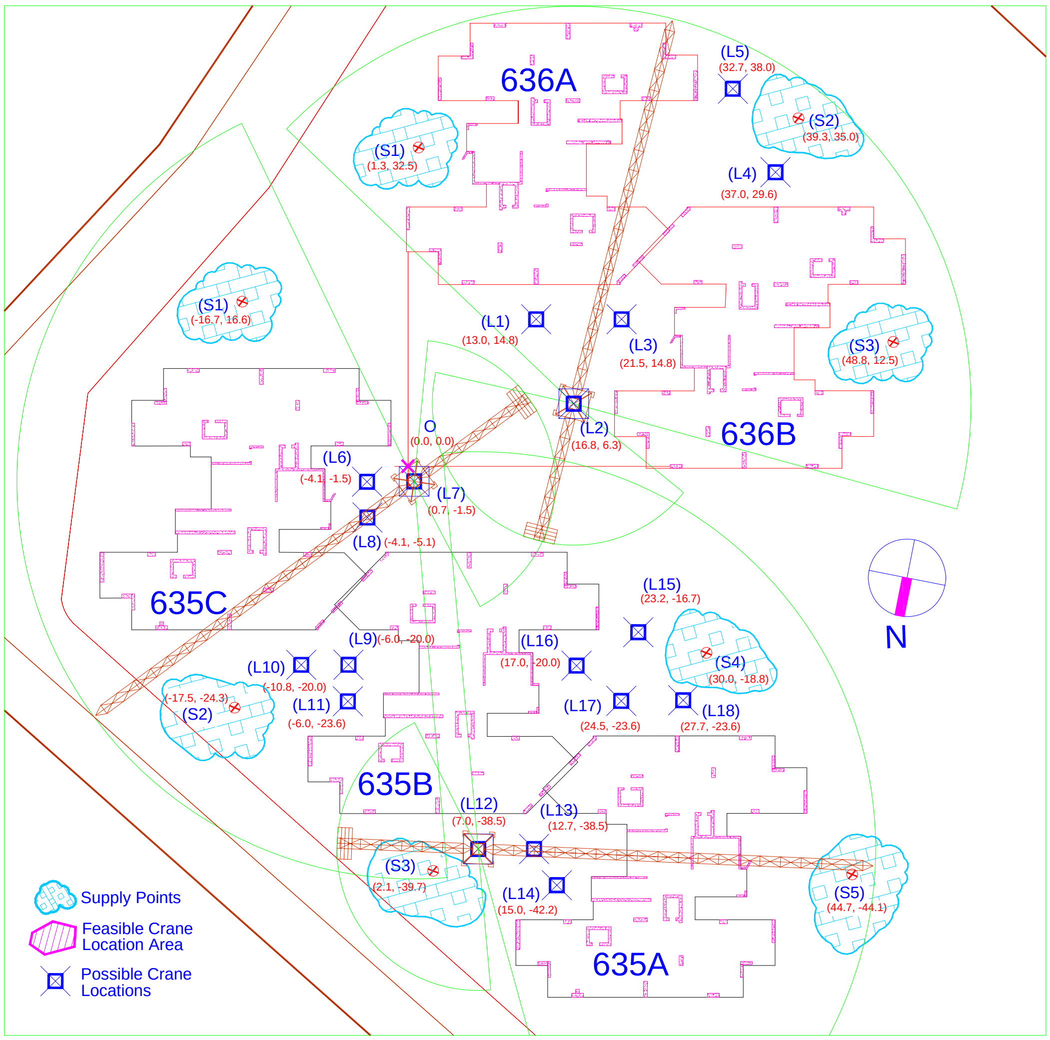


Figure 5.34: Actual Tower Crane Layout of PUNGGOL Site

The assembling of the group of tower cranes is described below. First, a 400-ton mobile crane helps to assembly the tower crane at L_{12} from the side of the site. This tower crane is the used to assembly another tower crane at location L_7 and this tower crane, in turn, helps to assembly the tower crane at location L_2. The dismantling procedure is inverse order. Tower crane at location L_7 helps to dismantle the one at location L_2. Tower crane at L_{12} dismantles the tower crane at location L_7. Lastly, the mobile crane helps to dismantle this tower crane at L_{12} from the North roadside. In fact, the optimised tower crane layout had been proposed to be used before by the site engineer, with his own reasoning. However, he then preferred the actual tower crane layout than the optimised one since he thought it would be easier for the mobile crane to assembly or dismantle the tower crane from the roadside than from the middle of the site. The optimal total hoisting time is 377.187 minutes. The GA performance of Block 635A-B-C of the optimised test and the actual site layout test is presented in Fig. 5.30.

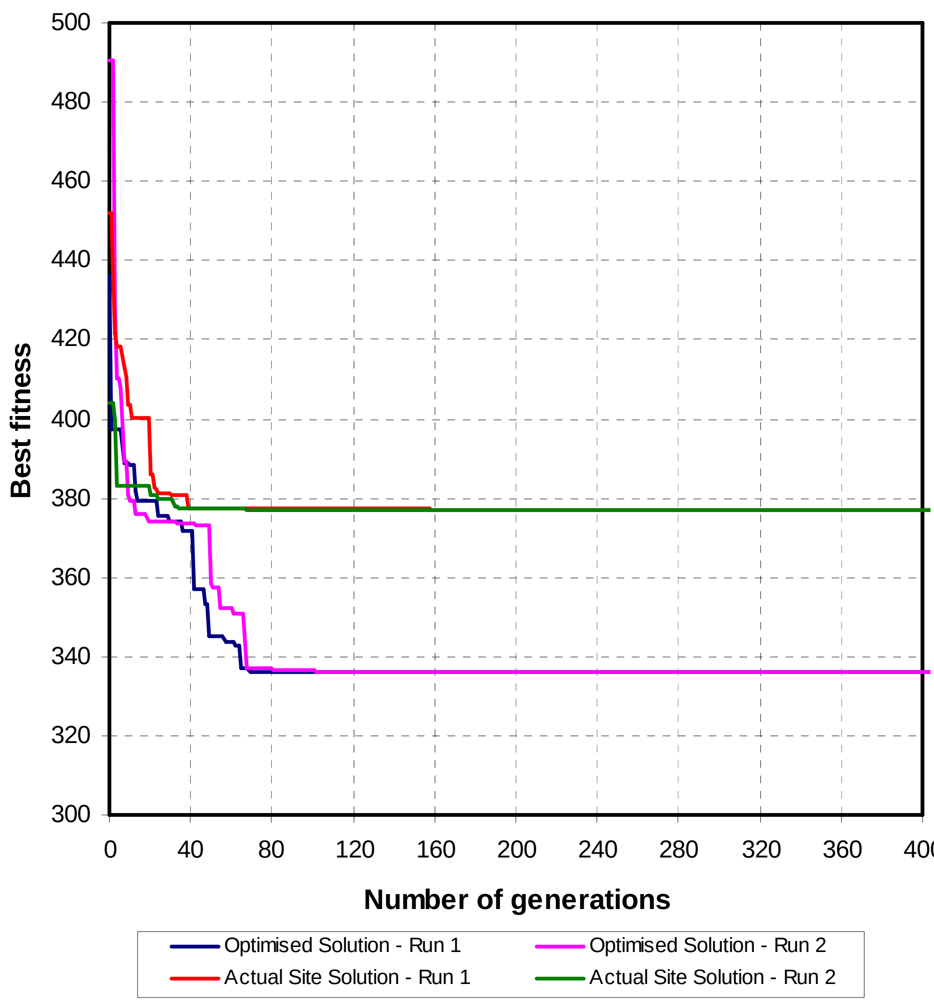


Figure 5.35: GA Performance of 2 Independent Runs For the Installation of Structural Precast Components in the 2nd Floors - Block 635A&B&C - PUNGGOL Site (the Optimised Solution vs. the Actual Solution Chosen on Site)

The difference of the fitness between the optimised solution and the actual solution chosen on site is (377.187 – 336.252) = 40.935 minute. Thus the program can help to save about 40.935*100/336.252 = 12.17 % of total hoisting time.

CHAPTER VI: CONCLUSIONS, ASSESSMENTS AND RECOMMENDATIONS FOR FURTHER STUDY

6.1 Conclusions

The Genetic Algorithm (GA) model as proposed in this study can successfully solve the Crane Location Problem (CLP) with multiple cranes, multiple possible crane locations, multiple supply points, and with real configurations of available cranes in the company's list.

The GA model performs best on the problems with (a) small number of possible supply points and (b) when all the cranes in the database can satisfy the lift capacity requirements. The former implies that a large number of possible supply points (e.g. N_{supply} = 10) can create a huge search space. The latter can be explained by the sparseness of the solution space in section 3.4.3. The crane capacity constraints make the solution space discontinuous and thus cause difficulty for GA during its search. This is a typical characteristic of most optimization methods; adding more constraints correlates to increased difficulty in solving the problem.

The disadvantage of the present method is that, although genetic algorithms are conceptually simple and well-suited to problems with a mix of continuous and discrete variables, the implementation is far from trivial. There is actually a great deal of work (as described in chapter 4) to implementing GA on real problems with large search spaces.

6.2 Assessments

Efforts have been made to build a computer program to aid practitioners finding the optimise solution for the CLP. This has been the first program developed to solve the CLP for the high-rise precast construction projects. The program is also one of few programs that can deal with multiple tower cranes. Moreover, the program takes into account the effects of the safe installation order (the lifting sequence), the balance movements of tower crane, the various configurations of different tower crane models available, and the inter-dependent relation between tower crane locations and supply point locations. These mentioned features make the program practical and relevant to real site practices. The following potential benefits of the CLP model are identified:

- The GA model will be integrated with an application program called I-LIFT that aims to provide aids for practitioners during the lift planning process in precast construction project. The GA model will act as an optimiser to choose the best solution from the available ones. Thus, the GA model is a helpful tool for expert practitioners (site engineers/ project managers etc.) to solve the CLP with quantitative assessment on related factors.
- The program also can be used as an instruction tool for training new and inexperienced site practitioners about lift management with regards to tower crane operations, safety aspect, and management of facilities layout.
- The final site facility layout reports, the task assignment reports and the recommended lift sequence can be used directly to manage various related tasks on site. For example, the information can be used to schedule the installations jobs and the plan for supplier, to issue equipment rental plan, to arrange for other site activities to ensure the work efficiency of tower crane, and to prepare for the crane(s) foundation.

6.3 Recommendations for Further Study

Further improvements of the model can be carried out to enhance the GA performance such that the program can find a suitable solution within an acceptable time. What can be done to improve the GA performance? Improving the operator's algorithm may be a good solution. The 1-point combinational crossover can be upgraded to 2-point combinational crossover since the 2-point crossover seems to work better in some similar NP-hard combinational problems. Other advanced method is to hybridize the representation. Combining the genetic algorithms with another search algorithm such as hill climbing should provide immediate improvement.

Further developments of the model are also strongly recommended. These developments can expand the scope of applications of the program in the following directions: (1) Control multiple crane collisions; (2) Control the supply point capacities and (3) Extent the scope of the program for crane work in the conventional cast in-situ projects.

(1) Control multiple crane collisions: Develop a sub-program to calculate the crane conflict indicator between two tower cranes according to the proposed approach as discussed in section 3.1.5.3. With this part, the GA model can be used to control collisions thus possible accidents can be avoided during crane operations on site.

(2) Control the supply point capacities: Currently, the supply points are assumed to have unrestricted capacity. In precast construction, the limitations of the supply point can be handled by either the just-in-time method (lifting the modules directly from trucks) or by using the auxiliary lifting equipment (such as a mobile crane, or a truck carrier forklift) to help to move the lifting modules from the temporary storage to its delivery points on site. However, for better management of supply points, their capacity can be taken into account by an additional module integrated into the objective function of the main program. Basically, this improvement will create a

higher control of facility resources, i.e. the capacity of supply points. This part can be an important and crucial improvement in the application of the program to choose tower cranes for the cast in situ projects.

(3) Extend the scope of the program for the conventional cast in-situ concrete projects: This part is actually another objective function with the presence of the material flow matrix between each pair of supply point and demand point (the demand point is not the exact installation point as in the precast concrete projects). The material flow should be the number of lifts calculated based on the weight of the material transported.

Other minor improvements include:

(a) Controlling the number of crane options: The user can predetermine the number of cranes that will be used in a particular project rather than let the program calculate all the possible alternatives and recommend the number of cranes. The default maximum number of cranes is the number of available cranes in the database.

(b) Expanding the scope of the objective function to include another option of the crane rental cost: This part can be implemented by introducing the matrix of crane rental cost and other related cost such as cost for assembly and dismantling operations for each tower crane model in the database. If the market prices of the cranes are available, the program can give the results with the minimum cost involved.

REFERENCES

1. Ackoff, R. L., A Concept of Corporate Planning. John Wiley & Son, New York. 1970.
2. Ackley, D., A Connectionist Machine for Genetic Hill Climbing, Kluwer Academic Publisher, Boston, 1987.
3. Al-Hussein M., Alkass S., and Moselhi O. A computer integrated system for crane selection. Proceedings of the 6th international conference on Civil and Structural Engineering Computing, volume: Development in computer aided design and modelling for civil engineering, CIVIL-COMP Press, Edinburgh, U.K., pp. 43–48. 1995.
4. Al-Hussein M., Alkass S., and Moselhi O. An algorithm for mobile crane selection and location on construction sites. Construction of innovation, vol. 1, pp. 91-105. 2001.
5. Alander, J. An Indexed Bibliography of Genetic Algorithms. ftp://ftp.uwasa.fi, 1996.
6. Alexandre F., Cardeira C., Charpillet F., Mammeri Z., and Portmann M.C. Compu-search methodologies II : Scheduling using genetic algorithms and artificial neural networks. In The Planning and Scheduling of Production Systems : Methodologies and Applications, ed by A. Artiba and S. E. Elmaghraby, pp. 301-335. Chapman & Hall, London. 1997.
7. Alkass, A., Aronian, A., and Moselhi, O. Computer-aided equipment selection for transporting and placing concrete. Journal of Construction Engineering and Management, ASCE, 119(3), 445–465. 1994.

8. Bethke, A. D. Genetic Algorithms as Function Optimizers. Doctoral Dissertation University of Michigan, 1980.

9. British Standards Institution (BSI). Code of Practice for Safe use of cranes (mobile cranes, tower cranes and derrick cranes). CP 3010: 1972.

10. Chalabi, A.F. and Yandow, C. Crane, and Expert system for optimal tower crane selection and placement. Sixth Conference on Computing in Civil Engineering, Atlanta, GA, pp. 290 - 297. 1989.

11. Chan, W.T., David Chua, K.H., and Kannan, G. Construction Resource Scheduling with genetic algorithms. Journal of Construction Engineering and Management. Pp. 125-132. June, 1996.

12. Choi, C.W. and Harris, F.C. A model for determining optimum crane position. Proceedings of the Institution of Civil Engineers, vol. 90, June, pp. 627–634. 1991.

13. Cooke, T.H. Concrete Pumping and Spraying. Thomas Telford, London. 1990.

14. Construction Industry Research and Information Association (CIRIA). Crane Stability on Site. John Laing Construction Limited and Sir William Halcrow & Partners Ltd. Special publication 131, London, UK. 1996.

15. Croner@CCH Ltd. Mobile towers. Construction risks special report. Issue 45, UK. Jan. 2002.

16. De Jong, K.N. Genetic Algorithms: 25 years perspective. Computational Intelligence: Imitating Life, pp. 125-134, 1994.

17. Deitel, H.M. and Deitel, P.J. (4^{th} Ed.) C++: How to program. Prentice Hall, New Jersey. 2003.

18. Dickie, D.E. and Short, D. Crane handbook, revised U.K. ed. Butterworth, London. 1981.

19. Dickie, D.E. and Campbell, D.H. (5th Printing.) Mobile crane manual. Construction safety association of Ontario, Toronto, Ontario, Canada. 1993.

20. Dieleman, B. (President of Las Vegas-based Jake's Crane & Rigging). Selecting a tower crane. Cranes Today. Foots Cray, Iss. 327, pp. 31, Mar., 2002.

21. Emsley, M. W. Discussion on a model for the selection of the optimum crane for construction sites. Proceedings of Institution of Civil Engineers., Structures and Buildings, 94, 503–504. 1992.

22. Falkenauer, E. Genetic Algorithms and grouping Problems. John Wiley and Sons, USA, 1998.

23. Farrell, C.W., and Hover, K.C. Computerised crane selection and placement for the construction site. Proceedings of 4th International Conference on Civil and Structural Engineering Computing, CIVIL-COMP Press, Edinburgh, U.K., 1. 1989.

24. Furusaka, S. and Gray, C. A model for the selection of the optimum crane for construction sites. Journal of Construction Management and Economics, 1984, 2, pp. 157 – 176. 1984.

25. Gen, M. and Cheng, R., Genetic Algorithms and Engineering Design, John Wiley and Sons, USA (and Canada), 1996.

26. Goldberg, D. E. Computer-aided gas pipeline operation using genetic algorithms and rule learning. Doctoral dissertation, Uni. of Michigan, 1983.

27. Goldberg, D. E. Genetic Algorithms in Search, Optimization, and Machine Learning. Addison-Wesley, Reading, Mass. 1989a.

28. Goldberg, D. E., Genetic Algorithms and Walsh Functions_ Part I_ A Gentle Introduction Complex Systems 3, pp. 139-152, 1989b.

29. Goldberg, D. E., Genetic Algorithms and Walsh Functions Part II_ Deception and its Analysis Complex Systems 3, pp. 153-171, 1989c.

30. Goldberg, D. E. A note on Boltzmann tournament selection for genetic algorithms and population oriented simulated annealing. Complex Systems 4, 445-460. 1990.

31. Goldberg, D. E. The design of Innovation – Lesson from and for Competent Genetic Algorithms. Kluwer Academic Publishers. USA. 2002.

32. Gray, C. Build ability – the construction contribution. Occasional Paper No. 29, London, Chartered Institute of Building. 1983.

33. Gray, C. and Little, J. A systematic approach to the selection of an appropriate crane for a construction site. Journal of Construction Management and Economics, vol. 3, pp. 121-144. 1985.

34. Gray, C. Crane location and selection by computer. Fourth International Symposium on Robotics and Artificial Intelligence in Building Construction, Haifa, 1987.

35. Grefenstette, J. J. Deception considered harmful. In Foundations of Genetic Algorithms *2*, D. Whitley (Ed.), San Mateo, CA: Morgan Kaufmann. 1993.

36. Griffis, F. H. (Bud), John V. Farr and Morris M. D. Construction Planning for Engineers. McGraw-Hill Higher Education. America. 2000.

37. Hamiani, A. and Popescu, G. Consite: a knowledge-based expert system for site layout. Computing in civil engineering: micro computers to supercomputers, K.M Will, ed., ASCE, New York, pp. 248-256. 1988.

38. Handa, V. and Lang, B. Construction site planning. Construction Canada, 30(3), pp. 43-49. 1988.

39. Hanna, A.S. Selectcrane: An expert system for optimum Crane selection. Proceedings of the 1st Congress on Computing in Civil Engineering, Washington, DC, pp. 958 - 963. 1994.

40. Hanna, A.S. and Lotfallah W.B. A fuzzy logic approach to the selection of cranes. Automation in Construction, 8, pp. 597-608. 1999.

41. Harris, F. C. Modern construction equipment and methods. Longman Science and Technology, London, U.K. 1989.

42. Harris, F.C. (2nd ed.). Modern Construction and Ground Engineering Equipment and Methods. Essex, England: Longman Scientific & Technical. 1994.

43. Harris, F. C., and McCaffer, R. Management of contractor's plant. Technical Information Service, Chartered Inst. of Building, U.K., No. 127. 1991.

44. Haupt, R. L., and Haupt S. E. Practical genetic algorithms. Wiley, New York, USA, 1998.

45. Herbert, P. F. Vertical movement of materials on high rise building. Building Technology and Management, vol. 12, pp. 6-10. April 1974.

46. Holland, J. H. Adaptation in natural and artificial systems, University of Michigan Press, Ann Arbor, Mich, 1975.

47. Housing Development Board. Construction site – Safety. The Board, Singapore. 1993.

48. Illingworth, J. R. (1st Ed.) Construction Methods and Planning. E & FN Spon, London, 1993.

49. Illingworth, J. R. (2nd Ed.) Construction Methods and Planning. E & FN Spon, London, 2000.

50. Ingber, L., and Rosen, B., Genetic algorithms and very fast simulated reannealing: A comparison, Mathematics and Computer Modeling **16** (11), pp. 87-100. 1992.

51. Ingber, L., Simulated annealing: Practice versus theory. Journal of Mathematics and Computer Modeling, 18, pp. 29-57. 1993.

52. International Construction. Construction Towers. IC reports on the innovative and fast changing tower crane market. Chicago, vol. 38, issue 7, pp. 18-20. July, 1999.

53. Jaramillo, H. J., Bhadury, J., and Batta, R. On the use of genetic algorithms to solve location problems. Computers & Operations Research, 29, pp. 761-779, 2002.

54. Jenkins, W.M. On the application of natural algorithm to structural design optimization. Engrg. Struct., 19(4), 302–308. 1997.

55. King, C. and Schexnayder, C.J. Tower crane selection at Jonathon W. Rogers surface water treatment plan extension. Practice Periodical of Structural Design and Construction, vol. 7, 1, February, 1, pp. 5-8. 2002.

56. Koenig, A. and Moo, B.E. Accelerated C++: Practical programming by example. Addison-Wesley. 2000.

57. Kogan, J. Crane Design – Theory and Calculations of Reliability. Jerusalem, Israel: Israel Universities Press. 1976.

58. Lam and Yin. Genetic Algorithm-Based Approach for Transportation Optimization Problems. In the practical handbook of genetic algorithms applications, ed. by Lance Chambers, pp. Chapman & Hall/CRC, Florida, USA. 2001.

59. Lance Chambers. (2nd ed.). The practical handbook of Genetic Algorithms Applications. Chapman & Hall/CRC, Florida, USA. 2001.

60. Li, H. and Love, P.E.D. Site-level facilities layout using genetic algorithms. Journal of Computing in Civil Engineering, 12(4), 227–31. 1988.

61. Masterton, G. and Wilson, R. The Planning and Design of Concrete Mixes for Transporting, Placing and Finishing. CIRIA Report. 1995.

62. Mehlhorn, K. Data Structures and Algorithms. Berlin: Springer-Verlag. 1984.

63. Michael, J. M., Saad, H. A., and Hongbo Y. Genetics Algorithms for Construction Site Layout in Project Planning. Journal of construction engineering and management, vol. 128, 5, pp. 418-426. October 2002.

64. Michalewicz, Z. Genetic Algorithm + Data Structure = Evolution Programs, 2nd ed., Springer-Verlag, New York, 1994.

65. Mitchell, M. An Introduction to Genetic Algorithms. The MIT Press, USA. 1997.

66. Mitchell, M. and Forrest S. Royal Road Functions. In Handbook of Evolutionary Computation. T. Back, D. Fogel, and Z. Michalewicz (editors), Oxford: Oxford University Press. 1998.

67. National Institute of Standards and Technology (NIST). Dictionary of algorithms and data structures. USA. http://www.nist.gov/dads/HTML

68. New Zealand Geotechnical Society. 2003. Draft for comment. Guidelines for the classification and field description of soils and rocks for engineering purposes. Website: http://www.nzgeotechsoc.org.nz/index.htm

69. Nunnally, S.W. (4th Ed.) Construction Methods and Management. Pp. 451-482, Prentice hall, New Jersey. 1998.

70. Nunnally, S.W. (2nd Ed.) Managing Construction Equipment. Pp. 127-146, Prentice hall, New Jersey. 2000.

71. PCI erectors committee. (1st Ed.) Erection safety for precast and prestressed concrete. pp. 105-111, USA: Precast/Prestressed concrete institute. 1995.

72. Peurifoy, R.L. and Schexnayder C.J. (6th ed.) Construction Planning, Equipment, and Methods. Mc Graw Hill, USA. 2002.

73. Philip, M., Mahadevan N. and Varghese K. Optimization of construction site layout – a genetic algorithm approach. Computing in Civil Engineering. Proceedings of the 4th Congress held in Conjunction with A/E/C Systems ’97 in Philadelphia, PA, June, pp. 710–17. 1997.

74. Proverbs, D.G. and Holt G.D. Logistics of materials handling methods in high rise in-situ construction. International journal of physical distribution and Logistics Management, Vol. 29, 10, pp. 659 – 675. 1999.

75. Rodriguez-Ramos and Francis, R.L. Single crane Location Optimization. Journal of Structural Engineering. ASCE. Dec. 109. No. 4, pp. 387-397. 1983.

76. Sale, D.B. Crane safety on construction sites. ASCE manuals and reports on engineering practice. No 93. 1998.

77. Schaufelberger, J.E. Construction Equipment Management. pp. 233-250, Columbus, Ohio: Prentice Hall 17.7. 1999.

78. Sen, M.K. and Stoffa, P.L. Comparative analysis of simulated annealing and genetic algorithms: Theoretical aspects and asymptotic convergence. *Geophysics.* , (submitted) 1993.

79. Shapira, A. and Glascock, J.D. Culture of Using Mobile Cranes for Building Construction. Journal of Construction Engineering and Management, December 1996, pp. 298-307. 1996.

80. Shapira, A. and Schexnayder, J. Selection of mobile cranes for building construction projects. Journal of construction Management and Economics, 17, pp. 519-527. 1999.

81. Shapiro, H.I., Shapiro, J.P., and Shapiro, L.K. (2rd ed.). Cranes and Derricks. New York: McGraw-Hill. 1991.

82. Shapiro, H.I., Shapiro, J.P., and Shapiro, L.K. (3rd ed.). Cranes and Derricks. New York: McGraw-Hill. 1999.

83. Shawhney, A. and Mund, A. Adaptive Probabilistic Neural Network-based crane type selection system. Journal of Construction Engineering and Management, May/June 2002, pp. 265-273. 2002.

84. Tam, C.M., Thomas, K.L. Tong, and Wilson, K.W. Chan. Genetic Algorithm for Optimizing Supply Locations around Tower Crane. Journal of Construction Engineering and Management, July/August 2001, pp. 315-321. 2001.

85. Tam, C.M. and Thomas, K.L. Tong. GA-ANN Model for Optimizing the Locations of Tower Crane and Supply Points for High-rise Public Housing Construction. Journal of Construction Management and Economics, 21, pp. 257-266. 2003.

86. Tommelein, I.D. SightPlan – An expert system that models and augments human decision-making for designing construction site layouts. PhD thesis, Stanford University, Stanford, California, USA. 1989.

87. Tommelein, I. D., Levitt R. E., Hayes-Roth B. and Confrey T. SightPlan Experiments: Alternate Strategies for Site Layout Design. Journal of Computing in Civil Engineering, ASCE, 5(1), pp. 42-63. 1991

88. Vallings, H.G. (2rd ed.). Mechanisation in building. Applied Science, London. 1975.

89. Wall, M. B. A Genetic Algorithm for Resource-Constrained Scheduling. PhD Thesis, Massachusetts Institute of Technology. 1996.

90. Wall, M. B. GAlib – A C++ Library of Genetic Algorithm Components. http://lancet.mit.edu/ga/ , 1999.

91. Warszawski, A. Analysis of transportation methods in construction. Journal of Construction Division, ASCE, 99(1), pp. 191–202. 1973.

92. Warszawski, A. Decision model and expert system in construction management. Building and Environment, 20(4), pp. 201–210. 1985.

93. Warszawski, A. Expert system for crane selection. Journal of Construction Management and Economics, 8, pp. 179-190. 1990.

94. Warszawski, A. and Peled N. An expert System for crane selection and location. Fourth International Symposium on Robotics and Artificial Intelligence in Building Construction, Haifa, pp. 64-75. 1987.

95. Wijesundera, D.A. and Harris F.C. Computer simulation for materials handling in high rise construction. Proceedings of the International AMSE Conference on Modeling and Simulation, Sorrento, Italy, 4.4, pp. 81–95. 1986.

96. Wijesundera, D.A. and Harris F.C. The selection of materials handling methods in construction by simulation. Construction Management and Economics, 7, pp. 95–102. 1989.

97. Wijesundera, D.A., Olomolaiye, P.O., and Harris, F.C. Dynamic simulation applied to materials handling in high-rise construction. Computers and Structures, 41(6), pp. 1133–1139. 1991.

98. Zhang, P., Harris, F. C., Olomolaiye, P. O., and Goodwin, M. A simulation model for optimising the location of a single tower crane. Proc., 6th Int. Conf. on Civil and Structural Engineering Computing, Vol: Development in

computational techniques for civil engineering, CIVILCOMP Press, Edinburgh, U.K., pp. 25–32. 1995.

99. Zhang, P., Harris, F.C., and Olomolaiye, P. O. A computer based model for optimising the location of a single tower crane. Building Research and Informatics, 24(2), pp. 113–123, 1996.

100. Zhang, P., Harris, F.C., Olomolaiye, P.O. Location Optimization for a Group of Tower Cranes. Journal of Construction Engineering and Management, March/April 1999, pp.115-122. 1999.

101. Miscellaneous internet resources:

Emporis is a provider of building-related information.

Website: http://www.emporis.com/en/

GA Introduction:

Marek Obitko http://cs.felk.cvut.cz/~xobitko/ga/

Matt Sullivan http://www.cs.qub.ac.uk/~M.Sullivan/ga/ga1.html

APPENDIX A: PSEUDO-CODE FOR THE CUSTOMISED GENETIC OPERATORS

Due to the lengthy and complicated of the real code written in C++ (about 150 pages of codes), here below only presents the pseudo-codes for the customised genetic operators.

A.1 Customized Initialiser

// Starting Initializer Operator

Create a blank genome with the length L_{binary}

$(L_{binary} = N_{crane}*N_{location} + (N_{supply} + N_{crane})*N_{small\_group} + N_{crane}* N_{available})$

Create an integer array with the length $L_{integer} = 2*(N_{crane} + N_{small\_group})$.

Set all the alleles of the array to zero

// Assign value for CLG:

Create a permutation array of $N_{location}$ elements

Swap the array randomly $N_{location}$ times

For (int n = 0; n < N_{crane} ; n++) {

Assign the random value from the swapped array to CLG using the greedy algorithm

}

Transfer the assigned solution (in integer value) to binary representation

Map the binary representation of CLG into the blank genome

// Assign value for SPG:

Create a permutation array of N_{supply} elements

Swap the array randomly N_{supply} times

For (int n = 0; n < N_{small_group} ; n++) {

Assign random value from the swapped array to SPG using the random number generator.

}

Transfer the assigned solution (in integer value) to binary representation

Map the binary representation of SPG into the blank genome

// Assign value for CAG:

Create a permutation array of N_{crane} elements

Swap the array randomly N_{crane} times

For (int n = 0; n < N_{small_group} ; n++) {

Assign random value from the swapped array to CAG using the random number generator.

}

Transfer the assigned solution (in integer value) to binary representation

Map the binary representation of CAG into the blank genome

// Assign value for CDG:

Create a permutation array of $N_{available}$ elements

Swap the array randomly $N_{available}$ times

For (int n = 0; n < N_{crane} ; n++) {

Assign the random value from the swapped array to CDG using the greedy algorithm

}

Transfer the assigned solution (in integer value) to binary representation

Map the binary representation of CDG into the blank genome

// finish creating a chromosome

Place the chromosome to the initial population

IF $N_{chromosome} < N_{population}$ Then

Continue to create new chromosome

ELSE

Stop creating new chromosome.

End IF (End of Initializer)

Start to evaluate fitness of chromosome in the initial population

A.2 Customised Combinational Mutation

The pseudo code of the customised combinational mutation is as below.

// Starting Combinational Permutation Operator

Choose a child chromosome to perform permutation operation.

Calculate number of permutation point ($n_{mut} = p_{mut} * L_{integer}$)

IF ($n_{mut} \leq 0$) Then Do nothing.

ELSE IF ($0 < n_{mut} < 1$) Then

Perform permutation according to possibility of p_{mut}.

ELSE // Perform permutation according to $n_{mut} \geq 1$ (multiple mutating)

For (int n = 0; $n \leq n_{mut}$; n++) { Perform multiple mutation. }

RETURN new chromosome.

// End of mutation.

The pseudo code to perform a single permutation is as below.

// perform a single permutation

// after selecting a child chromosome to perform mutation

Generate a random number to choose the group of genes to perform mutation.

Find the corresponding group of genes (CLP, SPG, CAG or CDG)

IF (the group of genes to mutate is CLG or CDG) DO

Create a temporary array to store all possible solutions (A1)

Create another array to gather information from existing chromosome (A2)

Generate a combination array (A3) that rearranges A1 according to A2.

Randomly choose another group of genes in A3

Swap genetic material between the two groups of genes.

RETURN the swapped chromosome in binary representation.

IF (the group of genes to mutate is SPG or CAG) DO

Create a temporary array to store all possible solutions (A'1)

Randomly chosen a group of genes in A'1.

Swap genetic material between the two groups of genes.

RETURN the swapped chromosome in binary representation.

RETURN The swapped chromosome

//end of permutation.

When performing multiple mutations in the same chromosome ($n_{mut} \geq 1$), the greedy algorithms is also applied to ensure the most effective mutating procedure, i.e. to ensure one group of genes is mutated only once. This procedure is illustrated below.

// Perform multiple mutating when $n_{mut} \geq 1$

Create a permutation array of $L_{integer}$

For (int n = 0; $n \leq n_{mut}$; n++) {

Assign the random value from the swapped array to CDG using the greedy algorithms to specify the group of genes chosen

Perform permutation in chosen group of genes.

}

Return the swapped chromosome in binary representation

A.3 Customised Combinational Crossover

The pseudo code of combinational crossover is as below.

// Starting Combinational Crossover Operator

Choose a pair of chromosomes to perform permutation operation according to their fitness. (Those chromosomes are called parents)

Randomly choose the crossover site using the random number generator

Map the crossover site to the corresponding group of genes (CLP, SPG, CAG or CDG)

Create new blank offspring chromosomes (1 or 2)

IF (the crossover site is in the group of CLG or CDG genes) DO

//Perform 1 point OPMX in the CLG or CDG

Select the substring at random (according to the crossover site)

Exchange substring between parents

Determine mapping relationship

Legalize offsprings with mapping relationship to create new offspring

Copy this new phenotype to empty chromosomes

// Exchange genetic material for all other groups of genes

Copy other genetic material from parents to fill in the offspring chromosomes

RETURN one or both two new offsprings.

IF (the crossover site is in the group of SPG or CAG genes) DO

//Perform 1 point crossover in the SPG or CAG

Exchange the genetic materials of those group of genes of the two parents at two sides of the crossover site.

Copy this new phenotype to blank offspring chromosomes

// Exchange genetic material for all other groups of genes

Copy other genetic material from parents to fill in the offspring chromosome

RETURN one or both two new offsprings.

// end of combinational crossover.

A.4 Sample Code of the Greedy Algorithm to Assign Initial Value for CLG

```
// randomly assign value for the location genes with the greedy algorithm
    for ( int n = 0; n < Ncrane; n++ ) {

        // generate new solution
        int flag1c = 1;
        while ( flag1c = = 1 ) {
            flag1c = 0;

            // generate random number in the allowable range
            Ini1Rand1[n] = GARandomInt( 0 , ( Nlocation-1-n ) );

            // check the value generated from the randon number generator
            if ( Ini1Rand1[ n ] > ( Nlocation -1 -n ) || Ini1Rand1[ n ] < 0 ) {
              flag1c =1;
            }  // end if
        } //end while

        // assign the solution for a new group of CLG
        Ini1Arr2[ n ] = Ini1Arr1[ Ini1Rand1[ n ] ];

        // shrink the temporary array (eliminate the chosen solution)
        for ( int p = Ini1Rand1[ n ]; p < ( Nlocation - n ); p++ ) {
            Ini1Arr1[ p ] = Ini1Arr1[ p+1 ];
        } //end of for

    } // end of for n
```

APPENDIX B: PUNGGOL SITE – POH LIAN PROJECT

B.1 PUNGGOL Site – Poh Lian Project

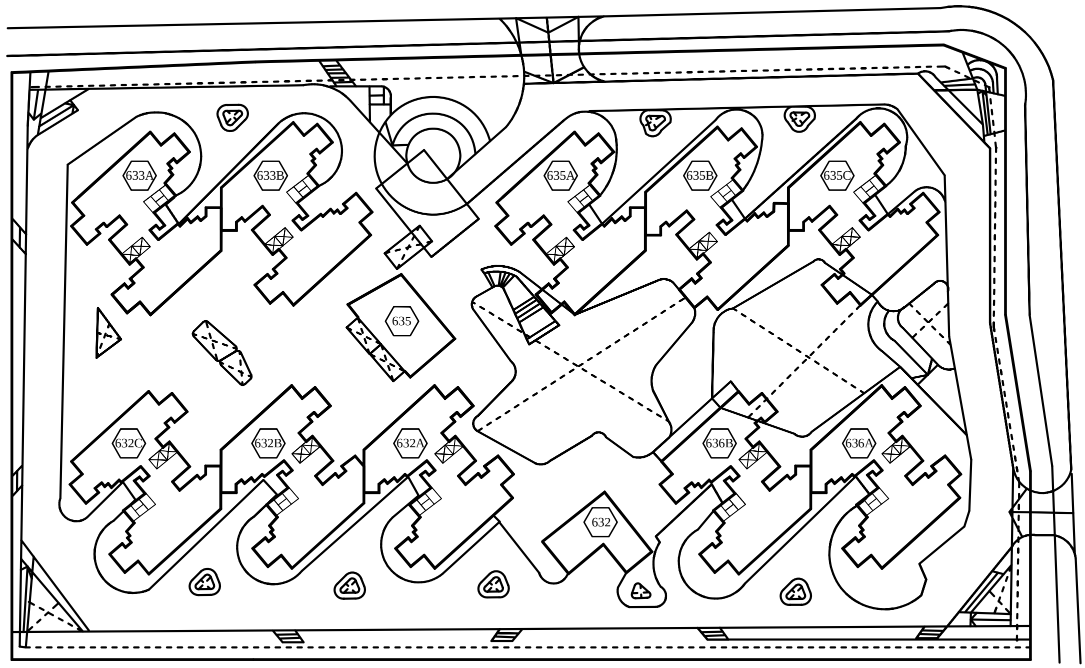


Figure B.2: Total Site Layout – Poh Lian Project

Since the site consists of two symmetric groups of blocks. The tower crane layout is planned for haft of the site, including block 636A&B and block 635A, B & C. Sample of the data of block 636A & 636B are presented in the flowing section.

B.2 Summary Data – Block 636A and 636B

There are total of 5 possible locations for tower crane to perform the lift jobs in block 636A & B. There are 3 supply points. All the lifting modules are grouped into 34 small groups. There are total of 6 tower cranes in the database (two Linden 2070 and four Linden 2074). There will be only one tower crane to work on both two blocks.

$N_{location}$ = 5; N_{supply} = 3; N_{small_group} = 34; $N_{available}$ = 6; N_{crane} = 1

B.2.1 Supply Point Locations' Coordinates

There are total of three supply points with coordinates as below.

XS[1] = 1.3; YS[1] = 32.5; ZS[1] = 1; XS[2] = 39.3; YS[2] = 35; ZS[2] = 1;
XS[3] = 48.8; YS[3] = 12.5; ZS[3] = 1;

B.2.2 Crane Locations' Coordinates

There are total of five possible locations for the tower crane with coordinates as below.
XL[1] = 13; YL[1] = 14.8; ZL[1] = 74.1; XL[2] = 16.8; YL[2] = 6.3; ZL[2] = 74.1;
XL[3] = 21.5; YL[3] = 14.8; ZL[3] = 74.1; XL[4] = 37; YL[4] = 29.6; ZL[4] = 74.1;
XL[5] = 32.7; YL[5] = 38; ZL[5] = 74.1;

B.2.3 Crane Database

LINDEN LC – 2070 (total 2)	***LINDEN LC-2074 (total 4)***
Height under hook 40.0 - 70.0 m	Height under hook 64.9 m
Radius 30.0 - 70.0 m	Radius 74 m
Maximum jib end load 2700-6000 kg (SR), 2500-7800 kg (SR/DR)	Maximum jib end load 2500 kg
Maximum load 6000 kg (SR) - 12000 kg (SR/DR)	Maximum load 12000 kg
Hoisting winch ES3 - 33 - 30: 33 KW	Hoisting winch ES3 - 33 – 30: 30 KW
Trolley CS3-4.5: 4.5 KW 1 speed (SR) or 2 speeds (SR/DR)	Trolley winch CS3 - 4.5: 4.5 KW
Slewing GR - 8.0: 80 Nm (40m) 2x80 Nm (60m) 3x80 Nm (70 m)	Slewing part GR - 8.0: 3 x 80 Nm 3 speed Rope drum with three layers 318 m
R 2.5 30 34 40	R 2.5 30 34 40
Q(SR/DR) 12 10.79 9.38 7.8	Q(SR/DR) 12 10.75 9.355 7.8

B.2.4 Number of Lifted Modules in each Small Group ($N_{ingroup}$)

All lifting modules are grouped into 34 groups. $n_{ingroup}$ is the number of modules in each groups. For example, the first 11 lifted modules in table B1 belong to group 1, the next 11 lifted modules are in the second group and so on. The first 6 groups are of the vertical structural precast elements including columns, shear walls and refuse chutes. The next 6 groups are of primary beams. Then there are two groups of secondary beams. The 15th group are the secondary beams of both the two blocks. The next 4 groups are of precast flanks. The 20th and 21st groups are some vertical elements of the next floor and so on.

$n_{ingroup}$[1] = 11; $n_{ingroup}$ [2] = 11; $n_{ingroup}$ [3] = 11; $n_{ingroup}$ [4] = 11; $n_{ingroup}$ [5] = 11; $n_{ingroup}$ [6] = 10; $n_{ingroup}$ [7] = 21; $n_{ingroup}$ [8] = 12; $n_{ingroup}$ [9] = 16; $n_{ingroup}$ [10] = 20; $n_{ingroup}$ [11] = 12; $n_{ingroup}$ [12] = 15; $n_{ingroup}$ [13] = 16; $n_{ingroup}$ [14] = 16;
$n_{ingroup}$ [15] = 20; $n_{ingroup}$ [16] = 27; $n_{ingroup}$ [17] = 24; $n_{ingroup}$ [18] = 26;
$n_{ingroup}$ [19] = 24; $n_{ingroup}$ [20] = 6; $n_{ingroup}$ [21] = 6; $n_{ingroup}$ [22] = 21;
$n_{ingroup}$ [23] = 12; $n_{ingroup}$ [24] = 16; $n_{ingroup}$ [25] = 20; $n_{ingroup}$ [26] = 12;
$n_{ingroup}$ [27] = 15; $n_{ingroup}$ [28] = 16; $n_{ingroup}$ [29] = 16; $n_{ingroup}$ [30] = 20;
$n_{ingroup}$ [31] = 27; $n_{ingroup}$ [32] = 24; $n_{ingroup}$ [33] = 26; $n_{ingroup}$ [34] = 24;

B.2.5 Lift priority of each small group

Lift priority of each small group refers to the installation order of that small group. The lift priority also mentions to the batch of the same type of lifted components. If two groups has the same priority, they are in the same batch, and maybe of the same type of lifted modules. In general buildings, the lifting priority starts from 1 (for elements in the bottom of the building) and increase according to the height of the installation points of the modules. Vertical structural elements usually starts a cycle of installations. For example, the group of columns, shear walls and lift cores has priority of 1. The primary beams have priority of 2, the 1st secondary beams have priority of 3, the rest beams have priority of 4. The precast planks have priority of 5. Then a new floor starts.

Priority[1] = 1; Priority[2] = 1; Priority[3] = 1; Priority[4] = 1; Priority[5] = 1; Priority[6] = 1; Priority[7] = 2; Priority[8] = 2; Priority[9] = 2; Priority[10] = 2; Priority[11] = 2; Priority[12] = 2; Priority[13] = 3; Priority[14] = 3; Priority[15] = 4; Priority[16] = 5; Priority[17] = 5; Priority[18] = 5; Priority[19] = 5; Priority[20] = 6; Priority[21] = 6; Priority[22] = 7; Priority[23] = 7; Priority[24] = 7; Priority[25] = 7; Priority[26] = 7; Priority[27] = 7; Priority[28] = 8; Priority[29] = 8; Priority[30] = 9; Priority[31] = 10; Priority[32] = 10; Priority[33] = 10; Priority[34] = 10

B.2.6 Installation Locations of Precast Elements

The installation locations and the weight of the structural precast elements are calculated from the shop drawings and tabulated in table B1 below. Based on these information, the GA model will test for the crane reach requirement (eq. 4.22) and the crane capacity (e.q. 4.23) for each lifted module to ensure its safe installations.

Table B1: Installation Locations of Precast Elements

Block 636A					Block 636B				
Columns, Walls and Core Lifts: (13 and 14th floors)									
Name	Installation Location			Weight	**Name**	Installation Location			Weight
Columns	X	Y	Z	Q	**Column**	X	Y	Z	Q
1	0	24.95	34.38	4.968	**34**	20.95	6.45	34.38	4.968
2	3.01	21.3	34.38	5.4	**35**	23.96	2.8	34.38	5.4
3	5.05	25.9	34.38	2.304	**36**	26	7.4	34.38	2.304
4	6.05	18.5	34.38	3.456	**37**	27	0	34.38	3.456
5	9.25	22	34.38	2.88	**38**	30.2	3.5	34.38	2.88
6	12.9	19.1	34.38	4.608	**39**	33.85	0.6	34.38	4.608
7	16.95	22.35	34.38	2.592	**40**	40.7	0	34.38	3.456
8	17.6	24.45	34.38	6.39	**41**	38.55	5.95	34.38	6.39
9	20.45	25.9	34.38	2.304	**42**	41.4	7.4	34.38	2.304
10	21.45	18.8	34.38	2.7	**43**	46.75	6.45	34.38	4.968
11	23.15	20.6	34.38	3.024	**44**	43.77	2.85	34.38	5.4
12	13.4	26.2	34.38	2.16	**45**	34.35	7.7	34.38	2.16
13	10.18	27.45	34.38	7.938	**46**	31.13	8.95	34.38	7.938
14	11.4	30.25	34.38	5.151	**47**	32.35	11.75	34.38	5.151
15	7.19	29.55	34.38	8.524	**48**	28.14	11.05	34.38	8.524
16	5.9	31.6	34.38	1.733	**49**	26.85	13.1	34.38	1.733
17	6.26	34.5	34.38	2.088	**50**	27.21	16	34.38	2.088
18	15.92	28.05	34.38	5.976	**51**	36.87	9.55	34.38	5.976
19	18.2	32.72	34.38	6.05	**52**	39.15	14.22	34.38	6.05
20	19.2	35	34.38	6.05	**53**	40.15	16.5	34.38	6.05
21	13.35	35.8	34.38	7.938	**54**	34.3	17.3	34.38	7.938
22	16.6	37	34.38	4.032	**55**	37.55	18.5	34.38	4.032
23	22.8	38.65	34.38	6.39	**56**	43.75	20.15	34.38	6.39
24	23.95	37.2	34.38	2.034	**57**	44.9	18.7	34.38	2.034
25	28.95	38.5	34.38	8.64	**58**	49.9	20	34.38	8.64
26	26.05	41.08	34.38	6.336	**59**	47	22.58	34.38	6.336
27	22.95	44.3	34.38	4.608	**60**	43.9	25.8	34.38	4.608
28	16.1	44	34.38	4.608	**61**	37.05	25.5	34.38	4.608
29	12.5	41.1	34.38	2.88	**62**	33.45	22.6	34.38	2.88
30	8.25	37.2	34.38	2.304	**63**	29.2	18.7	34.38	2.304
31	3.2	38.15	34.38	4.968	**64**	27.95	25.8	34.38	2.7
32	6.17	41.75	34.38	5.4	**65**	26.25	24	34.38	3.024
33	9.25	44.6	34.38	3.456					
Primary Beams									
Name	Installation Location			Weight	**Name**	Installation Location			Weight
Beams	X	Y	Z	Q	**Beams**	X	Y	Z	Q
66	29	40.5	37.18	0.6	**115**	49.95	22	37.18	0.6
67	28.05	41.3	37.18	1.3	**116**	49	22.8	37.18	1.3
68	25.8	43.65	37.18	0.9	**117**	46.75	25.15	37.18	0.9
69	24.6	44.45	37.18	1.3	**118**	45.55	25.95	37.18	1.3
70	19.4	44.45	37.18	2.8	**119**	40.35	25.95	37.18	2.8
71	26.55	37	37.18	2.1	**120**	47.5	18.5	37.18	2.1
72	21.2	36.3	37.18	1.1	**121**	42.15	17.8	37.18	1.1
73	21.45	33.7	37.18	0.3	**122**	42.4	15.2	37.18	0.3
74	19.7	37.15	37.18	0.35	**123**	40.65	18.65	37.18	0.35

Name	Installation Location			Weight	**Name**	Installation Location			Weight
Beams	X	Y	Z	Q	**Beams**	X	Y	Z	Q
75	18.4	36.9	37.18	0.9	**124**	39.35	18.4	37.18	0.9
76	17.2	35.82	37.18	0.4	**125**	38.15	17.32	37.18	0.4
77	16.05	40.05	37.18	2.4	**126**	37	21.55	37.18	2.4
78	12.85	44.45	37.18	2.8	**127**	32.6	26.1	37.18	3.9
79	7.45	44.45	37.18	1.3	**128**	27.15	24.8	37.18	0.6
80	6.4	43.45	37.18	0.9	**129**	28.15	22.65	37.18	2.65
81	4.2	41.25	37.18	1.3	**130**	24.4	19.7	37.18	1.33
82	3.2	40.1	37.18	0.9	**131**	27.2	18.5	37.18	1.5
83	5.6	37	37.18	2.1	**132**	31.45	18.5	37.18	1.73
84	10.5	37	37.18	1.73	**133**	33.5	20.3	37.18	1.3
85	12.55	38.8	37.18	1.3	**134**	36.05	18.3	37.18	0.6
86	15.1	36.8	37.18	0.6	**135**	30.6	15.95	37.18	1.95
87	9.65	34.45	37.18	1.95	**136**	26.95	14.35	37.18	1
88	6	32.85	37.18	1	**137**	29.95	12.55	37.18	1.32
89	9	31.05	37.18	1.32	**138**	37.4	16.35	37.18	0.35
90	16.45	34.85	37.18	0.35	**139**	36.9	15.25	37.18	2.1
91	15.95	33.75	37.18	0.5	**140**	37.2	11.75	37.18	1.1
92	16.25	30.25	37.18	2.1	**141**	38.75	8.1	37.18	0.25
93	17.8	26.6	37.18	1.1	**142**	37.4	7.4	37.18	0.6
94	16.45	25.9	37.18	0.25	**143**	36.2	7.75	37.18	0.35
95	15.25	26.25	37.18	0.6	**144**	34.95	8.5	37.18	0.18
96	14	27	37.18	0.35	**145**	34.5	9.4	37.18	0.41
97	13.55	27.9	37.18	0.18	**146**	32.85	7.75	37.18	1.73
98	11.9	26.25	37.18	0.41	**147**	28.25	7.5	37.18	2.1
99	7.3	26	37.18	1.73	**148**	23.35	7.5	37.18	0.9
100	2.4	26	37.18	2.1	**149**	20.95	4.4	37.18	1.3
101	0	22.9	37.18	0.9	**150**	21.95	3.3	37.18	0.9
102	1	21.8	37.18	1.3	**151**	24.15	1	37.18	1.3
103	3.2	19.5	37.18	0.9	**152**	25.2	0	37.18	2.8
104	4.25	18.5	37.18	1.3	**153**	30.6	0	37.18	1.3
105	9.65	18.5	37.18	2.8	**154**	30.2	5.7	37.18	2.4
106	9.25	24.2	37.18	1.3	**155**	33.85	4.55	37.18	3.9
107	12.9	23.05	37.18	2.4	**156**	37.05	0	37.18	2.8
108	17.05	18.5	37.18	3.9	**157**	42.5	0	37.18	1.3
109	16.5	23.05	37.18	0.4	**158**	43.55	1	37.18	0.9
110	20.9	22.1	37.18	2.65	**159**	45.75	3.3	37.18	1.3
111	22.35	26	37.18	1.5	**160**	46.75	4.4	37.18	0.9
112	25	24.9	37.18	1.33	**161**	44.2	7.5	37.18	2.1
113	22.3	19.75	37.18	0.6					
114	24.7	22.25	37.18	1.4					
Secondary Beam 1									
Name	Installation Location			Weight	**Name**	Installation Location			Weight
Beams	X	Y	Z	Q	**Beams**	X	Y	Z	Q
162	25.8	39.1	37.38	1.5	**178**	46.75	20.6	37.38	1.5
163	19.7	41.9	37.38	1.9	**179**	40.65	23.4	37.38	1.9
164	22.45	37	37.38	0.9	**180**	43.4	18.5	37.38	0.9
165	22.45	35.9	37.38	0.6	**181**	43.4	17.4	37.38	0.6

166	12.55	42.9	37.38	1.35	**182**	33.5	24.4	37.38	1.35
167	6.4	39.1	37.38	1.5	**183**	29.45	20.4	37.38	1.5
168	11.35	35.7	37.38	1.2	**184**	32.3	17.2	37.38	1.2
169	11.35	33	37.38	1.15	**185**	32.3	14.5	37.38	1.15
170	9.05	30.05	37.38	1.1	**186**	30	11.55	37.38	1.1
171	8.05	27.3	37.38	1.08	**187**	29	8.8	37.38	1.08
172	3.2	23.9	37.38	1.5	**188**	24.15	5.4	37.38	1.5
173	9.25	20.1	37.38	1.1	**189**	30.2	1.6	37.38	1.1
174	16.5	20.5	37.38	1.4	**190**	37.4	2.6	37.38	1.9
175	20.15	24.15	37.38	0.82	**191**	43.55	5.4	37.38	1.5
176	19	26	37.38	0.9	**192**	39.95	7.5	37.38	0.9
177	19	27.1	37.38	0.6	**193**	39.95	8.6	37.38	0.6
Secondary Beam 2									
Name	Installation Location			Weight	**Name**	Installation Location			Weight
Beams	X	Y	Z	Q	**Beams**	X	Y	Z	Q
194	23.85	39.3	37.38	1.6	**198**	44.8	20.8	37.38	1.6
195	9.45	39.3	37.38	2.25	**199**	41.6	5.2	37.38	1.6
196	13.7	32.65	37.38	2.1	**200**	34.65	14.15	37.38	2.1
197	6.2	23.7	37.38	2.25	**201**	27.15	5.2	37.38	2.25
Secondary Beams 3									
202	23.65	38.2	37.38	0.7	**206**	44.6	19.7	37.38	0.7
203	8.55	38.2	37.38	0.7	**207**	41.45	6.3	37.38	0.7
204	13.35	30.25	37.38	1.2	**208**	34.3	11.75	37.38	1.2
205	5.35	24.8	37.38	0.7	**209**	26.3	6.3	37.38	0.7
Secondary beams 4									
210	14.75	30.9	37.58	1.1	**212**	35.7	12.4	37.58	1.1
211	14.75	29.65	37.58	0.8	**213**	35.7	11.15	37.58	0.8
Precast Planks									
Name	Installation Location			Weight	**Name**	Installation Location			Weight
	X	Y	Z	Q		X	Y	Z	Q
214	27.3	39.8	37.98	1.662	**265**	48.25	21.3	37.98	1.662
215	27.3	37.85	37.98	0.681	**266**	48.25	19.35	37.98	0.681
216	24.5	41.9	37.98	2.676	**267**	45.45	23.4	37.98	2.676
217	22.05	41.9	37.98	2.676	**268**	43	23.4	37.98	2.676
218	20.25	41.9	37.98	1.21	**269**	41.2	23.4	37.98	1.21
219	24.75	38.2	37.98	0.734	**270**	45.7	19.7	37.98	0.734
220	22.9	38.2	37.98	0.583	**271**	43.85	19.7	37.98	0.583
221	22.4	36.35	37.98	0.435	**272**	43.35	17.85	37.98	0.435
222	19.2	35.55	37.98	0.963	**273**	40.15	17.05	37.98	0.963
223	17.9	38.15	37.98	1.9	**274**	38.85	19.65	37.98	1.9
224	17.9	40.7	37.98	1.9	**275**	38.85	22.2	37.98	1.9
225	17.9	43.2	37.98	1.9	**276**	38.85	24.7	37.98	1.9
226	15.75	35.8	37.98	0.825	**277**	36.7	17.3	37.98	0.825
227	14.3	38.15	37.98	1.9	**278**	35.25	19.65	37.98	1.9
228	14.3	40.7	37.98	1.9	**279**	35.25	22.2	37.98	1.9
229	14.3	43.2	37.98	1.9	**280**	35.25	24.7	37.98	1.9
230	7.7	41.9	37.98	2.676	**281**	29.42	24.15	37.98	2.024
231	10.15	41.9	37.98	2.676	**282**	32	24.15	37.98	2

232	11.95	41.9	37.98	1.21	**283**	25.6	21.35	37.98	2.327
233	4.88	39.8	37.98	1.662	**284**	31.45	20.35	37.98	3.168
234	4.88	37.85	37.98	0.681	**285**	28.65	20.35	37.98	1.226
235	10.55	39.2	37.98	1.415	**286**	32.75	17.2	37.98	0.435
236	7.5	39.2	37.98	0.734	**287**	29.95	14.6	37.98	2.57
237	11.8	35.7	37.98	0.435	**288**	29.95	12.95	37.98	0.99
238	9	33.1	37.98	2.57	**289**	34.65	14.75	37.98	1.02
239	9	31.45	37.98	0.99	**290**	35.75	13.3	37.98	1
240	13.7	33.25	37.98	1.02	**291**	33.55	10.95	37.98	2
241	14.8	31.8	37.98	1	**292**	29.6	8.8	37.98	0.435
242	12.6	29.45	37.98	2	**293**	28.3	6.3	37.98	1.415
243	8.65	27.3	37.98	0.435	**294**	25.25	6.3	37.98	0.734
244	7.35	24.8	37.98	1.415	**295**	22.65	4.7	37.98	1.662
Name	Installation Location			Weight	**Name**	Installation Location			Weight
	X	Y	Z	Q		X	Y	Z	Q
245	4.3	24.8	37.98	0.734	**296**	22.65	6.65	37.98	0.681
246	1.7	23.2	37.98	1.662	**297**	25.45	2.6	37.98	2.676
247	1.7	25.15	37.98	0.681	**298**	27.95	2.6	37.98	2.676
248	4.5	21.1	37.98	2.676	**299**	29.7	2.6	37.98	1.21
249	7	21.1	37.98	2.676	**300**	32.1	6.35	37.98	1.9
250	8.75	21.1	37.98	1.21	**301**	32.1	3.8	37.98	1.9
251	11.15	24.85	37.98	1.9	**302**	32.1	1.3	37.98	1.9
252	11.15	22.3	37.98	1.9	**303**	36.8	8.75	37.98	0.963
253	11.15	19.8	37.98	1.9	**304**	35.65	6.35	37.98	1.9
254	15.85	27.25	37.98	0.963	**305**	35.65	3.8	37.98	1.9
255	14.7	24.85	37.98	1.9	**306**	35.65	1.3	37.98	1.9
256	14.7	22.3	37.98	1.9	**307**	38.6	4.5	37.98	0.424
257	14.7	19.8	37.98	1.9	**308**	38	2.65	37.98	2.676
258	17.65	23	37.98	0.424	**309**	39.8	2.65	37.98	2.676
259	17.75	20.45	37.98	2.024	**310**	42.25	2.65	37.98	1.21
260	20.15	20.45	37.98	2	**311**	42.55	6.3	37.98	0.734
261	18.95	26.55	37.98	0.435	**312**	40.6	6.3	37.98	0.583
262	19.45	24.35	37.98	0.83	**313**	45	4.7	37.98	1.662
263	20.95	24.35	37.98	0.951	**314**	45	6.65	37.98	0.681
264	23.8	23.2	37.98	2.327					
Columns, Walls and Core Lifts in 14th floor.									
Name	Installation Location			Weight	**Name**	Installation Location			Weight
Beams	X	Y	Z	Q	**Beams**	X	Y	Z	Q
315	17.6	24.45	37.3	6.39	**321**	38.55	5.95	37.3	6.39
316	10.18	27.45	37.3	7.938	**322**	31.13	8.95	37.3	7.938
317	18.2	32.72	37.3	6.05	**323**	39.15	14.22	37.3	6.05
318	19.2	35	37.3	6.05	**324**	40.15	16.5	37.3	6.05
319	13.35	35.8	37.3	7.938	**325**	34.3	17.3	37.3	7.938
320	22.8	38.65	37.3	6.39	**326**	43.75	20.15	37.3	6.39
Precast Beams in 14th floor.									
Name	Installation Location			Weight	**Name**	Installation Location			Weight
Beams	X	Y	Z	Q	**Beams**	X	Y	Z	Q
327	29	40.5	39.98	0.6	**376**	49.95	22	39.98	0.6

328	28.05	41.3	39.98	1.3	**377**	49	22.8	39.98	1.3
329	25.8	43.65	39.98	0.9	**378**	46.75	25.15	39.98	0.9
330	24.6	44.45	39.98	1.3	**379**	45.55	25.95	39.98	1.3
331	19.4	44.45	39.98	2.8	**380**	40.35	25.95	39.98	2.8
332	26.55	37	39.98	2.1	**381**	47.5	18.5	39.98	2.1
333	21.2	36.3	39.98	1.1	**382**	42.15	17.8	39.98	1.1
334	21.45	33.7	39.98	0.3	**383**	42.4	15.2	39.98	0.3
335	19.7	37.15	39.98	0.35	**384**	40.65	18.65	39.98	0.35
336	18.4	36.9	39.98	0.9	**385**	39.35	18.4	39.98	0.9
337	17.2	35.82	39.98	0.4	**386**	38.15	17.32	39.98	0.4
338	16.05	40.05	39.98	2.4	**387**	37	21.55	39.98	2.4
339	12.85	44.45	39.98	2.8	**388**	32.6	26.1	39.98	3.9
340	7.45	44.45	39.98	1.3	**389**	27.15	24.8	39.98	0.6
341	6.4	43.45	39.98	0.9	**390**	28.15	22.65	39.98	2.65
342	4.2	41.25	39.98	1.3	**391**	24.4	19.7	39.98	1.33
343	3.2	40.1	39.98	0.9	**392**	27.2	18.5	39.98	1.5
344	5.6	37	39.98	2.1	**393**	31.45	18.5	39.98	1.73
345	10.5	37	39.98	1.73	**394**	33.5	20.3	39.98	1.3
346	12.55	38.8	39.98	1.3	**395**	36.05	18.3	39.98	0.6
347	15.1	36.8	39.98	0.6	**396**	30.6	15.95	39.98	1.95
348	9.65	34.45	39.98	1.95	**397**	26.95	14.35	39.98	1
349	6	32.85	39.98	1	**398**	29.95	12.55	39.98	1.32
350	9	31.05	39.98	1.32	**399**	37.4	16.35	39.98	0.35
351	16.45	34.85	39.98	0.35	**400**	36.9	15.25	39.98	2.1
352	15.95	33.75	39.98	0.5	**401**	37.2	11.75	39.98	1.1
353	16.25	30.25	39.98	2.1	**402**	38.75	8.1	39.98	0.25
354	17.8	26.6	39.98	1.1	**403**	37.4	7.4	39.98	0.6
355	16.45	25.9	39.98	0.25	**404**	36.2	7.75	39.98	0.35
356	15.25	26.25	39.98	0.6	**405**	34.95	8.5	39.98	0.18
357	14	27	39.98	0.35	**406**	34.5	9.4	39.98	0.41
358	13.55	27.9	39.98	0.18	**407**	32.85	7.75	39.98	1.73
359	11.9	26.25	39.98	0.41	**408**	28.25	7.5	39.98	2.1
360	7.3	26	39.98	1.73	**409**	23.35	7.5	39.98	0.9
361	2.4	26	39.98	2.1	**410**	20.95	4.4	39.98	1.3
362	0	22.9	39.98	0.9	**411**	21.95	3.3	39.98	0.9
363	1	21.8	39.98	1.3	**412**	24.15	1	39.98	1.3
364	3.2	19.5	39.98	0.9	**413**	25.2	0	39.98	2.8
365	4.25	18.5	39.98	1.3	**414**	30.6	0	39.98	1.3
366	9.65	18.5	39.98	2.8	**415**	30.2	5.7	39.98	2.4
367	9.25	24.2	39.98	1.3	**416**	33.85	4.55	39.98	3.9
368	12.9	23.05	39.98	2.4	**417**	37.05	0	39.98	2.8
369	17.05	18.5	39.98	3.9	**418**	42.5	0	39.98	1.3
370	16.5	23.05	39.98	0.4	**419**	43.55	1	39.98	0.9
371	20.9	22.1	39.98	2.65	**420**	45.75	3.3	39.98	1.3
372	22.35	26	39.98	1.5	**421**	46.75	4.4	39.98	0.9
373	25	24.9	39.98	1.33	**422**	44.2	7.5	39.98	2.1
374	22.3	19.75	39.98	0.6					
375	24.7	22.25	39.98	1.4					
Secondary beam 1									
Name	Installation Location			Weight	**Name**	Installation Location			Weight

Beams	X	Y	Z	Q	Beams	X	Y	Z	Q
423	25.8	39.1	40.18	1.5	**439**	46.75	20.6	40.18	1.5
424	19.7	41.9	40.18	1.9	**440**	40.65	23.4	40.18	1.9
425	22.45	37	40.18	0.9	**441**	43.4	18.5	40.18	0.9
426	22.45	35.9	40.18	0.6	**442**	43.4	17.4	40.18	0.6
427	12.55	42.9	40.18	1.35	**443**	33.5	24.4	40.18	1.35
428	6.4	39.1	40.18	1.5	**444**	29.45	20.4	40.18	1.5
429	11.35	35.7	40.18	1.2	**445**	32.3	17.2	40.18	1.2
430	11.35	33	40.18	1.15	**446**	32.3	14.5	40.18	1.15
431	9.05	30.05	40.18	1.1	**447**	30	11.55	40.18	1.1
432	8.05	27.3	40.18	1.08	**448**	29	8.8	40.18	1.08
433	3.2	23.9	40.18	1.5	**449**	24.15	5.4	40.18	1.5
434	9.25	20.1	40.18	1.1	**450**	30.2	1.6	40.18	1.1
435	16.5	20.5	40.18	1.4	**451**	37.4	2.6	40.18	1.9
436	20.15	24.15	40.18	0.82	**452**	43.55	5.4	40.18	1.5
437	19	26	40.18	0.9	**453**	39.95	7.5	40.18	0.9
438	19	27.1	40.18	0.6	**454**	39.95	8.6	40.18	0.6
Secondary Beam 2									
455	23.85	39.3	40.18	1.6	**459**	44.8	20.8	40.18	1.6
456	9.45	39.3	40.18	2.25	**460**	41.6	5.2	40.18	1.6
457	13.7	32.65	40.18	2.1	**461**	34.65	14.15	40.18	2.1
458	6.2	23.7	40.18	2.25	**462**	27.15	5.2	40.18	2.25
Secondary Beams 3									
463	23.65	38.2	40.18	0.7	**467**	44.6	19.7	40.18	0.7
464	8.55	38.2	40.18	0.7	**468**	41.45	6.3	40.18	0.7
465	13.35	30.25	40.18	1.2	**469**	34.3	11.75	40.18	1.2
466	5.35	24.8	40.18	0.7	**470**	26.3	6.3	40.18	0.7
Secondary beams 4									
471	14.75	30.9	40.38	1.1	**473**	35.7	12.4	40.38	1.1
472	14.75	29.65	40.38	0.8	**474**	35.7	11.15	40.38	0.8
Precast Flank									
Name	Installation Location			Weight	**Name**	Installation Location			weight
Flanks	X	Y	Z	Q	**Flanks**	X	Y	Z	Q
475	27.3	39.8	40.78	1.662	**526**	48.25	21.3	40.78	1.662
476	27.3	37.85	40.78	0.681	**527**	48.25	19.35	40.78	0.681
477	24.5	41.9	40.78	2.676	**528**	45.45	23.4	40.78	2.676
478	22.05	41.9	40.78	2.676	**529**	43	23.4	40.78	2.676
479	20.25	41.9	40.78	1.21	**530**	41.2	23.4	40.78	1.21
480	24.75	38.2	40.78	0.734	**531**	45.7	19.7	40.78	0.734
481	22.9	38.2	40.78	0.583	**532**	43.85	19.7	40.78	0.583
482	22.4	36.35	40.78	0.435	**533**	43.35	17.85	40.78	0.435
483	19.2	35.55	40.78	0.963	**534**	40.15	17.05	40.78	0.963
484	17.9	38.15	40.78	1.9	**535**	38.85	19.65	40.78	1.9
485	17.9	40.7	40.78	1.9	**536**	38.85	22.2	40.78	1.9
486	17.9	43.2	40.78	1.9	**537**	38.85	24.7	40.78	1.9
487	15.75	35.8	40.78	0.825	**538**	36.7	17.3	40.78	0.825
488	14.3	38.15	40.78	1.9	**539**	35.25	19.65	40.78	1.9
489	14.3	40.7	40.78	1.9	**540**	35.25	22.2	40.78	1.9
Name	Installation Location			Weight	**Name**	Installation Location			Weight

Flanks	X	Y	Z	Q	Flanks	X	Y	Z	Q
490	14.3	43.2	40.78	1.9	**541**	35.25	24.7	40.78	1.9
491	7.7	41.9	40.78	2.676	**542**	29.42	24.15	40.78	2.024
492	10.15	41.9	40.78	2.676	**543**	32	24.15	40.78	2
493	11.95	41.9	40.78	1.21	**544**	25.6	21.35	40.78	2.327
494	4.88	39.8	40.78	1.662	**545**	31.45	20.35	40.78	3.168
495	4.88	37.85	40.78	0.681	**546**	28.65	20.35	40.78	1.226
496	10.55	39.2	40.78	1.415	**547**	32.75	17.2	40.78	0.435
497	7.5	39.2	40.78	0.734	**548**	29.95	14.6	40.78	2.57
498	11.8	35.7	40.78	0.435	**549**	29.95	12.95	40.78	0.99
499	9	33.1	40.78	2.57	**550**	34.65	14.75	40.78	1.02
500	9	31.45	40.78	0.99	**551**	35.75	13.3	40.78	1
501	13.7	33.25	40.78	1.02	**552**	33.55	10.95	40.78	2
502	14.8	31.8	40.78	1	**553**	29.6	8.8	40.78	0.435
503	12.6	29.45	40.78	2	**554**	28.3	6.3	40.78	1.415
504	8.65	27.3	40.78	0.435	**555**	25.25	6.3	40.78	0.734
505	7.35	24.8	40.78	1.415	**556**	22.65	4.7	40.78	1.662
506	4.3	24.8	40.78	0.734	**557**	22.65	6.65	40.78	0.681
507	1.7	23.2	40.78	1.662	**558**	25.45	2.6	40.78	2.676
508	1.7	25.15	40.78	0.681	**559**	27.95	2.6	40.78	2.676
509	4.5	21.1	40.78	2.676	**560**	29.7	2.6	40.78	1.21
510	7	21.1	40.78	2.676	**561**	32.1	6.35	40.78	1.9
511	8.75	21.1	40.78	1.21	**562**	32.1	3.8	40.78	1.9
512	11.15	24.85	40.78	1.9	**563**	32.1	1.3	40.78	1.9
513	11.15	22.3	40.78	1.9	**564**	36.8	8.75	40.78	0.963
514	11.15	19.8	40.78	1.9	**565**	35.65	6.35	40.78	1.9
515	15.85	27.25	40.78	0.963	**566**	35.65	3.8	40.78	1.9
516	14.7	24.85	40.78	1.9	**567**	35.65	1.3	40.78	1.9
517	14.7	22.3	40.78	1.9	**568**	38.6	4.5	40.78	0.424
518	14.7	19.8	40.78	1.9	**569**	38	2.65	40.78	2.676
519	17.65	23	40.78	0.424	**570**	39.8	2.65	40.78	2.676
520	17.75	20.45	40.78	2.024	**571**	42.25	2.65	40.78	1.21
521	20.15	20.45	40.78	2	**572**	42.55	6.3	40.78	0.734
522	18.95	26.55	40.78	0.435	**573**	40.6	6.3	40.78	0.583
523	19.45	24.35	40.78	0.83	**574**	45	4.7	40.78	1.662
524	20.95	24.35	40.78	0.951	**575**	45	6.65	40.78	0.681
525	23.8	23.2	40.78	2.327					