2013-07-10

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Mecham, Bradley R., "Modeling and Optimization of Space Use and Transportation for a 3D Walkable City" (2013). *All Theses and Dissertations*. 3693.
https://scholarsarchive.byu.edu/etd/3693

Modeling and Optimization of Space Use and Transportation for a 3D Walkable City

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A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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July 2013

ABSTRACT

Modeling and Optimization of Space Use and Transportation for a 3D Walkable City

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This thesis presents an investigation of a new three-dimensional urban form where walking distances are less than a half-mile and congestion is minimal. The car-free urban form investigated herein is a city composed of skyscrapers massively interconnected with skybridges at multiple levels. The investigation consists of optimizing space use arrangement, skybridge presence or absence, and elevator number to simultaneously minimize total travel time, skybridge light blockage, and elevator energy usage in the city. These objectives are evaluated using three objective functions, the most significant of which involves a three-dimensional, pedestrian-only, three-step version of the traditional four-step planning model. Optimal and diverse designs are discovered with a genetic algorithm that generates always-feasible designs and uses the maximin fitness function. The space use arrangements and travel times of four extreme designs are analyzed and discussed, and the overall results of the investigation are presented. Conclusions suggest that skybridges are beneficial in reducing travel time and that travel times are shorter in cities wherein space use is mixed vertically as well as horizontally.

Keywords: walkability, skybridge, land use optimization, greenplex, always-feasible designs

ACKNOWLEDGMENTS

Anyone who knows me well would agree that this thesis did not appear in a day, and that the list of those who contributed is not particularly short. I am therefore grateful for many, including those who trained me to write, the computer science and civil engineering teachers who taught me my technical skills, and Dr. Balling who led me through the actual thesis process. I am also grateful for Dr. Balling for his patience and persistence. Family, friends, and roommates have been a key to my success, and I thank them for their support. College and department staff have also been especially kind and helpful. Particularly, I express my thanks to the secretaries and the computer administrators. Most of all, I thank our Heavenly Father for His support. He placed in me all of the knowledge, wisdom, and talent I possess, and he gave me the drive to finish. Without Him, and without all of those others mentioned here, I would not have succeeded. Thank you!

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1 INTRODUCTION

Traffic congestion is the daily fare for commuters across the globe. Such inefficient travel leads to high costs, increased pollution, and wasted time. Most of these problems would disappear in a walkable car-free city; however, today's cities are generally not walkable. Walking distances are too long, and the ground level is often congested: traditional zoning ordinances separate, rather than mix, different space uses, which increases walking distance; and nearly all horizontal movement in today's cities is restricted to one, or possibly two, levels near ground level, which increases congestion. This thesis presents an investigation of a new three-dimensional urban form where walking distances are less than a half-mile and congestion is minimal.

The car-free urban form investigated herein is a city composed of skyscrapers massively interconnected with skybridges at multiple levels. The city should be small enough that the maximum walking distance is a half-mile, but large enough to contain most of the space uses that its citizens would visit in a typical day. Such an urban form can be called a "greenplex." The model greenplex used to investigate this new form accommodates 25,000 residents. All trips modeled are internal to the greenplex, freight movement is not considered, and only pedestrian traffic is allowed.

Transportation in a greenplex should be very efficient. Adding skybridges should reduce trip lengths and lead to shorter travel times. But minimum travel time is not the only objective in optimal greenplex design. A greenplex design specifies the arrangement of the spaces uses, the configuration of the skybridges, and the number and location of the elevators in the model. An optimal greenplex design will exhibit a balance between the transportation advantage offered by numerous skybridges and the amount of light blocked by these skybridges. It will also show a balance between improved vertical travel times and the amount of energy consumed by elevators in each building. An evolutionary search known as the genetic algorithm, that simultaneously optimizes space use and the transportation network, can discover such multiple-objective greenplex designs.

The search space explored by a naively implemented genetic algorithm is prohibitively large, even with a relatively small, 25,000-person model. However, preemptively eliminating infeasible designs makes the search practical. Infeasible designs are those that do not satisfy the space use constraints for the city. The problem formulation explained herein automatically eliminates infeasible greenplex designs and facilitates rapid solution discovery.

This thesis seeks to discover the advantages of three-dimensional space use and transportation, and to identify the trends in optimal greenplex design. The research shows that a three-dimensional transportation network greatly reduces travel time, and that optimal space use arrangement varies based on the location and quantity of skybridges and elevators.

This work is laid out in seven chapters. Chapter 2 reviews the related literature preceding this research. Chapter 3 discusses the details of the example optimization problem, including the greenplex modeled and the options for greenplex designs. Three objective functions are used to analyze greenplex designs. Chapter 4 explains the models for each objective function. Chapter 5 describes the optimization method, or the search for the optimal greenplex designs. Finally, Chapter 6 presents the results, and Chapter 7 presents the conclusions.

2 LITERATURE REVIEW

The literature review for this thesis covers three general areas. These areas are 1) pedestrian-based transportation models including horizontal models, vertical models, and 3D models, 2) genetic algorithms with always-feasible designs, and 3) methods for simultaneous optimization of space use and transportation in a city.

2.1 Pedestrian-based Transportation Models

Pedestrian-based transportation modeling is not new, and there are many advanced approaches for simulating pedestrian traffic in a variety of situations. For several reasons, the approach taken in this thesis differs from those in other available models. The main differences are in scale and dimension. Most other models are microscopic or mesoscopic models, wherein each pedestrian in the system is modeled individually and group dynamics are studied in the aggregate. The model used herein must be run thousands of times, so a microscopic or mesoscopic model would be infeasible. Further, the three-dimensional aspect of the model herein presents a context not seen in 2D or even current 3D applications. This section reviews the details of the current models. It consists of three parts: 1) Horizontal Pedestrian Transportation Models, 2) Vertical Pedestrian Transportation Models, and 3) Combined Horizontal and Vertical Transportation Models.

2.1.1 Horizontal Pedestrian Transportation Models

Horizontal pedestrian travel is usually modeled microscopically. The discrete choice model developed by Antonini et al. (2006), and the model of pedestrian behavior in crowded places recently developed by Koh and Zhou (2011) are typical of these microscopic models.

Not all models are microscopic, however. Papadimitriou et al. (2009) reviewed the existing models. They reported that while the majority of models are microscopic, many others use macroscopic principles, like fluid mechanics or traffic flow theory, to study pedestrian movement. Works like those of Huang et al. (2009), and Piccoli and Tosin (2011) are examples of this. The Highway Capacity Manual (Transportation Research Board 2010) contains the most general traffic flow principles of the macroscopic approach. It relates horizontal pedestrian density to walking speed and expected flow, and it explains the basic principles associated with efficient horizontal pedestrian travel. Chen et al. (2010) provided slightly more detail on speed and flow principles with a formula for travel speed for pedestrians given density.

2.1.2 Vertical Pedestrian Transportation Models

There are also many vertical pedestrian transportation models that simulate stairway, escalator, and/or elevator transportation. The algorithms for the most advanced and technical models are proprietary, but some information is still available through conference proceedings and technical papers. For example, Zhenshan and Yunli (2010) modified the classical theory for elevator traffic planning and proposed a model that improves quality of service while maintaining quantity of service. Many studies, such as one by Siikonen and Sorsa (2008), focus on modeling vertical transportation to prepare for emergency building evacuation analysis. In their report, Siikonen and Sorsa show the advantages of using elevators and express elevators to evacuate a tall building instead of using only the stairs.

2.1.3 Combined Horizontal and Vertical Pedestrian Transportation Models

Relatively few studies propose models that combine horizontal and vertical pedestrian transportation. In one study, Hamada et al. (2008) simulated horizontal and vertical movement in a high-rise building. They modeled the effect of mixing horizontal movement at each floor with traffic from the elevator system. Professional software modeling groups have developed programs that can model three-dimensional microscopic pedestrian transportation in places like a metro terminal, for example. State-of-the-art programs include STEPS (Scalici et al. 2006), Paxport (Mounsey et al. 2007), Legion (Zhou et al. 2009), and VisSim (Galiza et al. 2009).

2.2 Genetic Algorithms with Always-feasible Designs

The size of the search space for large optimization problems like the one in this thesis can be reduced by hundreds of orders of magnitude if the search is confined to feasible designs only. However, feasibility must be maintained throughout the crossover and mutation steps. Larrañaga et al. (1996) reviewed several genetic crossover and mutation methods that maintain feasibility. “Exchange mutation,” where genes in the chromosome simply swap positions, is a mutation method of particular note. They discuss several crossover methods, but more recent methods are available. For example, Deep and Mebrahtu (2011) review older algorithms, such as partially matched crossover, cycle crossover, modified crossover, and order crossover, before introducing and testing three new variants of order crossover. These order-based crossover methods are restricted to problems like the famous travelling salesman problem where every value must be used exactly once. Their report excludes crossover methods based on segment performance, such as heuristic crossover (Lin and Kernighan 1973) or edge recombinant crossover (Whitley et al. 1989).

2.3 Simultaneous Optimization of Space Use and Transportation for a City

Many researchers and urban planners have used learning and optimization algorithms when planning a city. Some have used optimization algorithms to optimize a single aspect of the city, either land use or transportation. For example, Almeida et al. (2008) and Raju et al. (1998) both used a backpropagation neural network to predict future behavior and trends in a city. Jia et al. (2009) used a genetic algorithm, an artificial bee colony algorithm, and a simulated annealing algorithm to optimize the road network in developing cities. And Pontius et al. (2008) compared numerous algorithms, some machine learning based and some not, and evaluated them on their effectiveness in predicting land change.

Others have simultaneously optimized both land use and transportation. For example, Balling et al. (2000) used a multi-objective genetic algorithm to optimize the land use and transportation in Orem and Provo, Utah. Lowry and Balling (2009) expanded previous results to apply the multi-objective genetic algorithm to a regional planning problem. Feng and Lin (1999) used a non-linear programming model and a genetic algorithm to generate sketch maps that optimize environment harmony and development efficiency for a new town area. They also simultaneously considered land use and transportation components in their model.

2.4 Thesis Contributions

The model in this thesis adds to these bodies of research in several ways. The walking-based transportation model covers an entire network of walkways, instead of the typical small selection of boulevards, sidewalks, or corridors. Instead of detailing the footpaths of every pedestrian in the city, the macroscopic model presented herein quickly assesses total network travel times, yielding an analysis that can be run hundreds of thousands of times in a few hours. Components of this macroscopic model include the walkway analysis formula presented by Chen et al (2010), and an abstraction of the paternoster elevator, recently studied and improved by the Hitachi Corporation (2013). The model in this thesis transcends representing the vertical transportation in a single building or the horizontal transportation over a few lower levels and represents the transportation across several horizontal levels and in dozens of buildings. It is more comprehensive and general than any pedestrian model previously studied.

The mutation method called "exchange mutation" is identical to the one used in this thesis. The crossover method in the model for this thesis differs significantly from all of the methods mentioned previously, because the method used herein allows for repetition of gene values in the chromosome (there are numerous genes representing office space, for example), which order-based encodings do not allow. The crossover method resembles most closely a combination of uniform crossover and a repair algorithm.

The transportation and land use optimization work done in this thesis is most similar to the work by Balling et al. (2000). Their two-dimensional land use and transportation optimization work is herein extended to three-dimensions.

3 EXAMPLE OPTIMIZATION PROBLEM

The example optimization problem considered in this thesis is a greenplex consisting of 25 buildings, as shown in plan view in Figure 3-1. Each building is 50m by 50m in plan, and the horizontal space between buildings is 25m. Thus, the base of the greenplex is 350m by 350m. Each building has a 25m by 25m central core where the elevator shafts are located. The number of floors in each building is listed in Figure 3-1. Note that there are 16 buildings with 39 floors, 8 buildings with 45 floors, and one building with 48 floors. Figure 3-1 also shows skybridges between the buildings. All skybridges are assumed to be 10m wide. An elevation view of the greenplex is shown in Figure 3-2. Skybridges are located at floors 9, 18, 27, and 36 above ground level. Note that each building has one floor below ground level. Also note that this city configuration is somewhat arbitrary: a larger city with larger buildings, or a smaller city with smaller buildings, could just as easily have been the example city chosen.

3.1 Optimization Variables

Usable space throughout the greenplex is divided into zones. The usable space in a building excludes the core, and for a particular floor is equal to $(50\text{m})^2$-$(25\text{m})^2$=1875m^2. Greenplex zones are three floors deep, as a middle option between one-floor zones, which would be small, and five-floor zones, which would be large. The total usable space per zone is equal to $(3)*(1875\text{m}^2)=5625\text{m}^2$. The total number of zones in the greenplex is

(16)*(39/3)+(8)*(45/3)+(1)*(48/3)=344. There is one integer-valued optimization variable for each zone. The possible integer values range from 1 to 16, corresponding to the different space uses listed in Table 3-1.

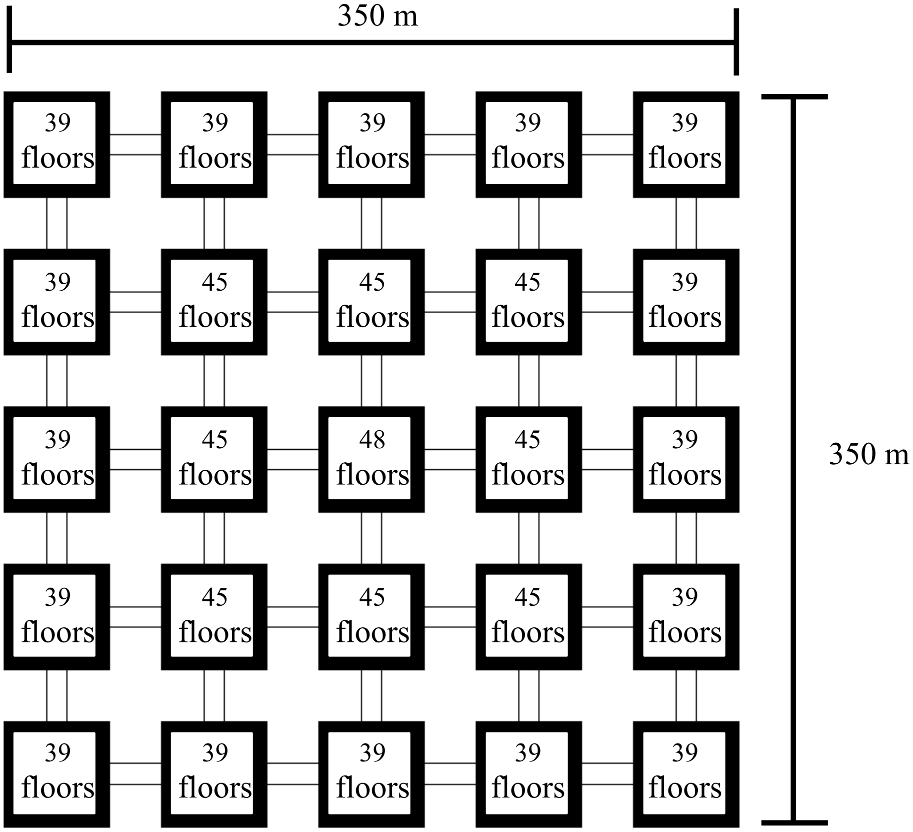


Figure 3-1: Plan view of model greenplex.

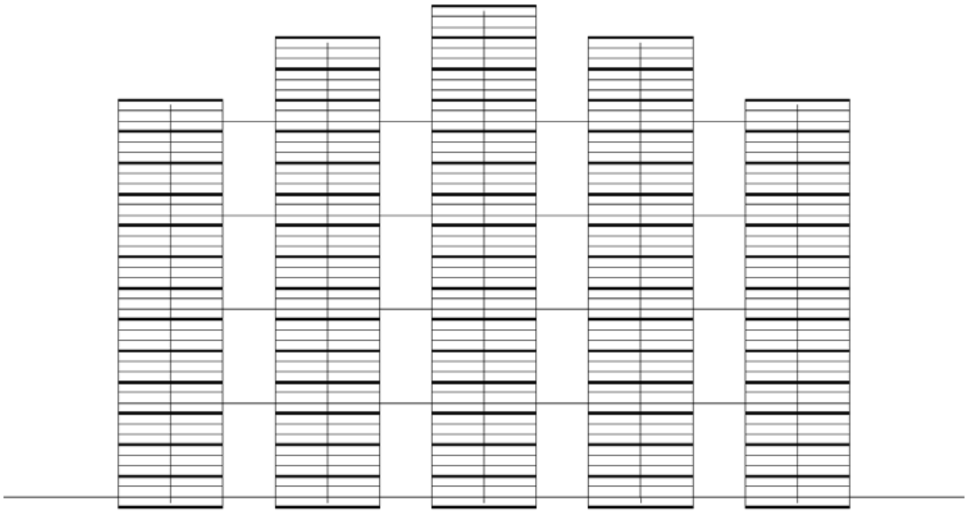


Figure 3-2: Profile view of fully connected model greenplex.

Table 3-1: Space Use Types

Variable Value	Space Use Type
1	Apartment
2	Residential Condominium
3	Multipurpose Recreational Facility
4	Athletic Club
5	Elementary School
6	Junior High School
7	High School
8	Church
9	Hospital
10	General Office Building
11	Medical-Dental Office Building
12	Research and Development Center
13	Shopping Center
14	Supermarket
15	High-Turnover (Sit-Down) Restaurant
16	Fast Food Restaurant

The space use types in Table 3-1 are a small but representative subset of the many land uses found in a typical city. Industrial land uses are omitted to reduce potential for pollution in the greenplex. Other common land uses are omitted or assimilated into the space uses shown to minimize the number of values for the optimization variable and reduce the search space size.

Agreeable to Figures 3-1 and 3-2, there are 160 skybridges in the example greenplex. There is one binary-valued optimization variable for each skybridge. A value of zero indicates that the associated skybridge is absent from the design, while a value of one indicates that the associated skybridge is present.

Each skyscraper core holds standard elevators and express elevators. Both standard and express elevator cars can carry 15 passengers. Each elevator, express or standard, is modeled as a circulating elevator system, or loop. Each loop occupies two parallel shafts, with multiple cars running upward in one shaft and multiple cars running downward in the other. Standard elevators stop at every floor, and there is one pair of standard elevator cars (one traveling upward and one traveling downward) per every three floors. Standard elevator loops span 9 consecutive floors of each building (floor 0 to floor 9, floor 9 to floor 18, etc.). Express elevators stop only at floors 0, 9, 18, 27, 36, and 45, and there is one pair of express elevator cars for each of these floors. Express elevator loops span the height of each building. In total, there are four optimization variables representing standard elevators for each of the 39-floor buildings, there are five optimization variables representing standard elevators for each of the 45-floor and 48-floor buildings, and there is one optimization variable representing express elevators for each of the buildings. This is a total of 134 optimization variables representing elevators. By design, in each skyscraper core there can be up to three standard elevator loops and up to three express elevator loops running parallel to each other. Therefore, each elevator optimization variable is integer-valued with values ranging from one to three, indicating the number of parallel loops in the represented span.

3.2 Constraints

A feasible design is one that meets the model constraints. The only constraints in this optimization problem are on space use. In order to accommodate the design population of 25,000 for the entire greenplex, it was determined that for a design to be feasible, the area of space for each use must equal the values listed in Table 3-2. The emphasis on obtaining accurate values for these requirements was very low. Rather, the demand for each type of zone in the model is a simple approximation of the demand in a typical city.

Table 3-2: Required Space Use in the Example Greenplex

Variable Value	Space Use	Zones in Model	Total m^2
1	Apartment	80	450,000
2	Residential Condominium	80	450,000
3	Multipurpose Recreational Facility	2	11,250
4	Athletic Club	2	11,250
5	Elementary School	3	16,875
6	Junior High School	3	16,875
7	High School	4	22,500
8	Church	6	33,750
9	Hospital	1	5,625
10	General Office Building	54	303,750
11	Medical-Dental Office Building	44	247,500
12	Research and Development Center	8	45,000
13	Shopping Center	45	253,125
14	Supermarket	9	50,625
15	High-Turnover (Sit-Down) Restaurant	2	11,250
16	Fast Food Restaurant	1	5,625
Total		344	1,935,000

Note that the sum of the areas in Table 2 is exactly equal to the sum of the areas for all zones: (344)*(5625m^2)=1,935,000m^2. Thus, a feasible plan will have exactly 80 zone variables with an integer value of one (apartment), 80 zone variables with an integer value of 2 (condominium), 2 zone variables with an integer value of 3 (recreational facility), etc.

3.3 Objectives

An optimal design is one that has minimum values for all of the model objective functions. There are three objective functions considered in the optimization problem. The first is the minimization of travel time of all trips during the evening peak period. The second is the minimization of energy usage by the elevators. The third is the minimization of natural light blockage by the skybridges. The evaluation of these three objective functions will be explained in Chapter 4.

4 MODELS FOR THE OBJECTIVE FUNCTIONS

This chapter explains the three objective functions mentioned in Section 3.3. The first objective function quantifies travel time performance in the model. The second objective function quantifies light blockage in the model. The third objective function quantifies energy usage in the model. No attempt is made to relate these three objective functions by a combinatory cost function. Rather, the value of each objective function is provided independently, so that designs that excel in any of the three areas may be identified. The three objective functions listed are discussed in turn.

4.1 Travel Time Objective Function

The first objective function is the minimization of travel time of all trips during the evening peak period. The evening peak period is modeled because apartments and condominiums—the origin of all trips in the model—generate more trips during the evening peak period than during the morning peak period. This objective function uses steps one, two, and four of the traditional four-step transportation planning model, and therefore it will be called a three-step model. This section explains the three steps of the model as implemented in this thesis.

4.1.1 Trip Generation

The first step is trip generation. Every zone in the model either produces or attracts trips. The number of trips produced or attracted corresponds to the space use type associated with each zone. Table 4-1 lists the different space use types and their corresponding number of trips. The first two space use types, apartments and condominiums, are called “productions,” and all other zones are called “attractions.” As shown in the table, empirical formulas dictate the number of trips associated with each space use. The formulas for all but the first two space uses are available in the Institute of Transportation Engineers (ITE) Trip Generation 7 report (2003). Note that X in these equations represents the number of thousands of square feet in the zone. All zones are the same size, so X always equals $(5625\text{m}^2)(10.7639\text{ft}^2/\text{m}^2)/(1000)=60.55$ thousand ft^2.

Table 4-1: Trip Generation in Model Greenplex

ITE Code - Space Use	Equation Used	Persons per Vehicle
220 - Apartment	$T(X) = 0.55X + 17.65$	1.67
230 - Residential Condominium	$\text{Ln}(T(X)) = 0.82\,\text{Ln}(X) + 0.32$	1.67
435 - Multipurpose Recreational Facility	$T(X) = 3.35X$	2.2
493 - Athletic Club	$T(X) = 5.76X$	2.2
520 - Elementary School	$T(X) = 3.13X$	1.67
522 - Junior High School	$T(X) = 1.19X$	1.67
530 - High School	$T(X) = 0.97X$	1.67
560 - Church	$T(X) = 0.66X$	2.2
610 - Hospital	$T(X) = 1.18X$	1.13
710 - General Office Building	$T(X) = 1.12X + 78.81$	1.13
720 - Medical-Dental Office Building	$T(X) = 3.72X$	1.37
760 - Research and Development Center	$\text{Ln}(T(X)) = 0.83\,\text{Ln}(X) + 1.06$	1.19
820 - Shopping Center	$\text{Ln}(T(X)) = 0.66\,\text{Ln}(X) + 3.4$	1.78
850 - Supermarket	$T(X) = 10.45X$	1.78
932 - High-Turnover Restaurant	$T(X) = 10.92X$	1.52
934 - Fast Food Restaurant	$T(X) = 34.64X$	1.67

Many of the R^2 values for these equations are low or not given. However, the intent of the model is only to analyze general principles, so approximate trip generation values are acceptable.

The formulas shown for the first two spaces were obtained from ITE Trip Generation 8 (2008). The X required in these equations is the number of dwelling units in the zone. An average assumption of 1,000 ft^2 per unit yields 60.55 units per zone. Though this is admittedly a poor assumption, the resulting number of trips is still higher for apartment zones than for condominium zones, which is the vital fact to model.

The vehicle trips given by the empirical formulas are converted to person trips using the persons-per-vehicle (ppv) factors in ITE Trip Generation 8 (2008). This conversion specifies greater numbers of trips than the computer model developed for this thesis can handle in a reasonable amount of time, so all of the values are divided by the productions' ppv factor (1.67) to reduce the total number of trips. Table 4-2 shows the final trip generation for each zone.

Table 4-2: Trip Generation in Model Greenplex

Space Use	Trips / Unit
Apartment	51
Residential Condominium	40
Multipurpose Recreational Facility	267
Athletic Club	459
Elementary School	190
Junior High School	72
High School	59
Church	53
Hospital	48
General Office Building	99
Medical-Dental Office Building	185
Research and Development Center	62
Shopping Center	479
Supermarket	674
High-Turnover (Sit-Down) Restaurant	602
Fast Food Restaurant	2097

4.1.2 Trip Distribution

The next step in the three-step model is trip distribution. Trips in the model originate at a production and terminate at an attraction. The gravity model distributes these trips. The gravity model generally distributes trips from an origin to the many possible destinations based on the number of trips attracted by a destination and the travel time from the origin to that destination. The model will distribute a proportion of each origin's trips to each relatively close, relatively attractive destination. The particular version of the gravity model used is shown in Equation 4-1.

$$T_{ij} = P_i * \frac{A_j * F_{ij}}{\sum_j A_j * F_{ij}} \tag{4-1}$$

T_{ij} represents the total number of trips from origin i to destination j. P_i represents the number of trips generated by origin i. A_j represents the number of trips drawn to destination j. F_{ij} is a travel time "friction factor," and is shown in Equation 4-2. It is traditionally the reciprocal of the travel time, t, from zone i to zone j, squared.

$$F_{ij} = \frac{1}{{t_{ij}}^2} \tag{4-2}$$

Travel time, t_{ij}, is the travel time along the shortest path from zone i to zone j across an empty network. A path is defined to be an ordered collection of links between the origin zone and destination zone. The model herein uses Dijkstra's algorithm (Cormen et al. 2001) to find these shortest paths. Dijkstra's algorithm is the traditional and fastest known algorithm for finding the shortest path across a network of links. It requires the travel time across each individual link as part of its input. The following paragraphs discuss the travel times across the two types of links, walkways and elevators.

Two types of walkways exist in the greenplex: skybridges and ground walkways. Travel time across these walkways is calculated according to the formula shown in Equation 4-3, based on work by Chen et al. (2010).

$$Travel\ time\ (min) = Length/(81.37\,m/\text{min}) \tag{4-3}$$

All skybridges and ground walkways are 25m long, and the distance from the edge of the skybridge to the building center is 25m. Thus the walkable length is 75m total, and the travel time along any walkway is (75m)/(81.37m/min)=0.92min, or 55.3 seconds.

There are two types of elevators in the model: standard and express. These elevators run according to the specifications in Tables 4-3 and 4-4, which are based on general industry performance measures at the time of this study (KONE Corporation 2012) (Stack Exchange Inc. 2011). According to these specifications and the dimensions of the current greenplex model, standard elevators arrive on a floor every 55.5 seconds and express elevators arrive on their respective floors every 26 seconds. Pedestrians arrive at the elevators an average of 23.8 seconds early for standard elevators, which is the standard elevator travel time divided by three (47.5s)/(3)=15.8s, plus one dwell time segment (8.0s). Therefore the total wait time before the elevator trip starts is (15.8s)+(8.0s)=23.8s. Three was used as the divisor instead of two to model an assumed tendency of pedestrians to hurry to catch the elevator. Using the same process, pedestrians are modeled to arrive 14 seconds early for express elevators: (18.0s)/(3)+(8.0s)=14.0s. They then traverse the link and wait an additional dwell-time phase before moving on. Thus the total travel time across an express elevator link is (14.0s)+(26.0s)=32s. Although in reality standard elevators deliver pedestrians to every floor, travel times are only calculated from zone center to zone center in the model, or every 3 floors. The travel time for a 3-floor trip is therefore (15.8s)+(55.5s)=71.3s. More than half of this time (40 seconds) is dwell time, and much of the rest of the time is spent accelerating and decelerating. A model that omitted unnecessary stops might improve travel times and be much more efficient; this model focused on keeping the calculations simple.

Table 4-3: Elevator Travel Rates

	Standard Elevator	Express Elevator
Travel Rate	1.0 m/s	6.0 m/s

Table 4-4: Elevator Performance Standards

Acceleration Rate	1.0 m/s^2
Deceleration Rate	1.0 m/s^2
Door Opening Time	2.0 s
Door Closing Time	2.5 s
Dwell Time	8.0 s
Capacity	15

These travel times across walkway and elevator links are the input for Dijkstra's algorithm. Dijkstra's algorithm determines the travel times along the shortest paths from every production to every attraction in the model. Those shortest travel times are the t_{ij} values for the gravity model. The gravity model then connects every trip from each production to a specific attraction.

4.1.3 Traffic Assignment

Once all of the trips have an origin and a destination, they must be assigned to a specific path. Trips are assigned incrementally to remove any bias based on the order in which trips are considered in the model. Trips are assigned to the shortest path available, again as computed by Dijkstra's algorithm. However, the formulas for link travel times must be modified to reflect congestion. For example, Equation 4-3 becomes Equation 4-4.

$$Travel\ time\ (min) = Length \Big/ \left(81.37 e^{-\frac{1}{2}\left(\frac{Density}{1.52}\right)^2} \right) \tag{4-4}$$

Skybridges are 10m wide, and ground walkways are modeled as being 50m wide. Density increases as trips are placed upon pathways, and travel times are updated accordingly.

Travel time calculations for elevator links are more complicated. The headway for an elevator is defined to be the difference in arrival time of two consecutive cars. For a standard elevator the headway is 55.5 seconds and for an express elevator the headway is 26 seconds. Delay is added to the travel time if the arriving car is already full. The total delay expected equals the headway, multiplied by the probability of a car being full. That probability is calculated using Equation 4-5.

The model runs over a 5-minute period, thus expecting 5 standard elevator cars per standard elevator link, and 11 express elevator cars per express elevator link. In Equation 4-5 therefore, *N* for the standard elevators is 165, and *N* for the express elevators is 75. Equation 4-6 shows the final probability formula for standard elevator cars, and Equation 4-7 shows the final probability formula for express elevator cars.

$$P(X = 15) = \frac{\binom{r}{15}\binom{s}{m-15}}{\binom{N}{m}} \tag{4-5}$$

r = the number of people assigned to the link

m = the number of spaces in each car

*N = m * the number of cars traveling the link during the evaluation period*

s = N - r

$$P(X = 15) = \frac{\binom{r}{15}}{\binom{165}{15}} \tag{4-6}$$

$$P(X = 15) = \frac{\binom{r}{15}}{\binom{75}{15}} \tag{4-7}$$

This probability, multiplied by the headway, is the total delay expected per trip across the link. The total travel time is the delay time plus the link travel time discussed in 4.1.2.

As travel times increase across walkways and along elevator links according to these models, the shortest path from a particular origin to its associated destination will change. To reflect these changes and remove bias associated with the order in which trips are considered, assignment is divided into eight incremental steps. There are eight increments because the numbers of productions and attractions are both divisible by eight, and eight is large enough to distribute the trips evenly and not increase running time unnecessarily. Each increment, approximately $1/8^{th}$ of the trips are assigned. Travel times are then updated and Dijkstra's algorithm determines the new shortest paths through the model. The next $1/8^{th}$ of the trips are then assigned. After eight increments, the assignment step is complete.

4.1.4 Total Travel Time

After the traffic assignment step, the total travel time for all trips in the model is calculated using the final travel times obtained for each link. The travel time objective function reports the total travel time divided by the total number of trips in the model.

4.2 Skybridge Light Blockage Objective Function

The second objective function to consider is the skybridge light blockage objective function. The cost of walkways in this model derives directly from the amount of light blocked. Skybridges are assumed to block a unit of light per skybridge. This simple objective function is therefore equal to the sum of the binary values of the skybridge optimization variables.

4.3 Elevator Energy Usage Objective Function

The third objective focuses on the minimization of energy usage by the elevators. Elevator energy usage reported in this model derives from the following assumptions. First, travel time at a constant speed requires no energy; only accelerating and decelerating require energy. Second, the amount of energy required to start or stop is 1/2 mv^2, where v is the target travel rate (1m/s for standard elevators and 6m/s for express elevators). Third, the riders' mass balances out in the system—some will go up and some will go down—and the mass of every car in the system is the same. This allows the mass term in 1/2 mv^2 to be dropped for the comparison. Finally, each elevator loop consists of two shafts, one going up and one going down, so the 1/2 term can be dropped. The total energy score for an elevator therefore equals

$$(v^2) * (\# \, of \, stops \, + \, \# \, of \, starts) \tag{4-8}$$

This total score differs for standard and express elevators. Express elevators have a target travel rate of 6.0m/s and stop only at floors 0, 9, 18, 27, 36, and 45. An express elevator will therefore start and stop four times in the shorter buildings and five times in the tallest building, yielding scores of 288 and 360 respectively, as per Equation 4-8. Standard elevators have a target travel rate of 1.0m/s and stop on every floor. As mentioned in 4.1.2, standard elevator loops span nine floors. Therefore each standard elevator makes nine starts and nine stops, for an 18-point contribution to the total. The total elevator energy usage in the greenplex is equal to the sum of all of these points, or (18)(# of standard elevators)+(288)(# of express elevators in shorter buildings)+(360)(# of express elevators in tallest building).

4.4 Objective Function Summary

The objective functions discussed in this chapter provide a way to assess the performance of a design with respect to each of the three objectives discussed in Chapter 3. The travel time objective function is based on the average travel time across the city. The elevator energy usage objective function is based on the total energy consumed by standard and express elevators as they start and stop during the evaluation period. And the skybridge light blockage objective function is based simply on the number of skybridges specified by the design. By evaluating each of these three objective functions, three independent measures of design performance can be obtained. These measures facilitate discovery of non-dominated greenplex designs, as is discussed in Chapter 5.

5 OPTIMIZATION METHODS

Greenplex designs are represented in genetic algorithms by chromosomes. The number of genes in a chromosome is exactly equal to the number of optimization variables. Thus, in the example optimization problem, the chromosome for a design consists of 344 integer-valued genes representing the zones, 160 binary-valued genes representing the skybridges, and 134 integer-valued genes representing the elevators (see 3.1). A typical chromosome can be visualized by referring to the image in Figure 5-1. This chapter discusses the creation, evaluation, reproduction, and survival of these chromosomes.

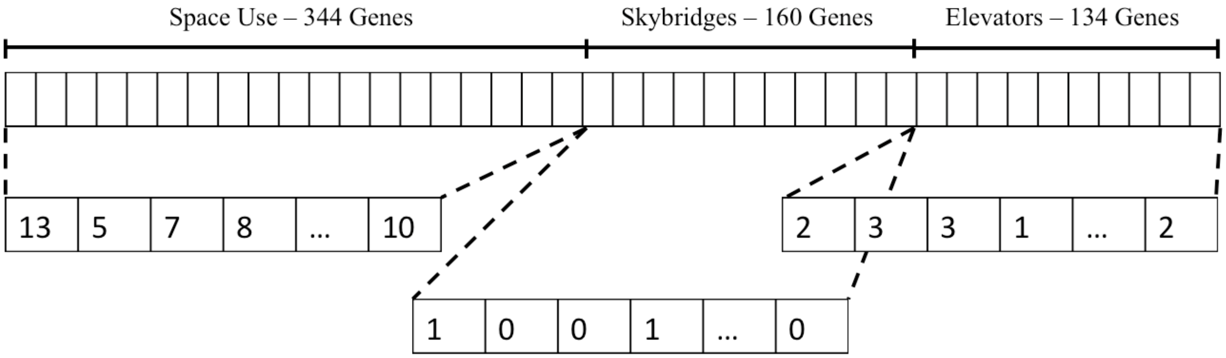


Figure 5-1: Visualization of a greenplex design chromosome.

5.1 Starting Generation

The first step of a genetic algorithm is the creation of a random starting generation (or population) of chromosomes. The values for the genes of each chromosome are random values between the minimum and maximum values for each type of gene, as shown in Table 5-1. The values for the genes representing space use zones must satisfy the space use constraints described in Section 3.2 to insure feasibility. The process for insuring feasibility is as follows. For each chromosome being randomly generated, bookkeeping is maintained to keep track of how many slots for each space use have been filled. The numbers of slots for each space use are initialized to the values in Table 3-2. As a random integer is generated for a particular gene, the number of slots for the corresponding space use is checked. If that number is greater than zero, the gene is assigned the random integer and the number of slots is decremented by one. If the number of slots is equal to zero, then another random integer is generated. Genes representing zones are assigned in random order.

Table 5-1: Chromosome Attributes

Gene Type	Number of Genes	Variable Type	Minimum	Maximum
Space Use	344	Integer-valued	1	16
Skybridge Presence	160	Binary-valued	0	1
Number of Elevators	134	Integer-valued	1	3

5.2 Chromosome Fitness

The second step in the genetic algorithm is to evaluate the fitness function for all of the chromosomes in the starting generation using the values of the objective functions described in

Chapter 4. The fitness function will be used later on to create successive generations. The maximin fitness function is used to reward both dominance and diversity (Balling 2003).

The maximin fitness function derives directly from the principle of dominance. Design *j* dominates design *i* if

$$\mathrm{f}_k^i \geq \mathrm{f}_k^j \text{ for } k = 1 \text{ to the number of objectives (3)} \tag{5-1}$$

where $\mathrm{f}_\mathrm{k}^\mathrm{i}$ = the value of the k^{th} objective function of chromosome *i* in the starting generation. Regardless of one's preferences about the relative importance of individual objectives, all can agree that a non-dominated design is better than a dominated design because it is better in every objective (See Figure 5-2).

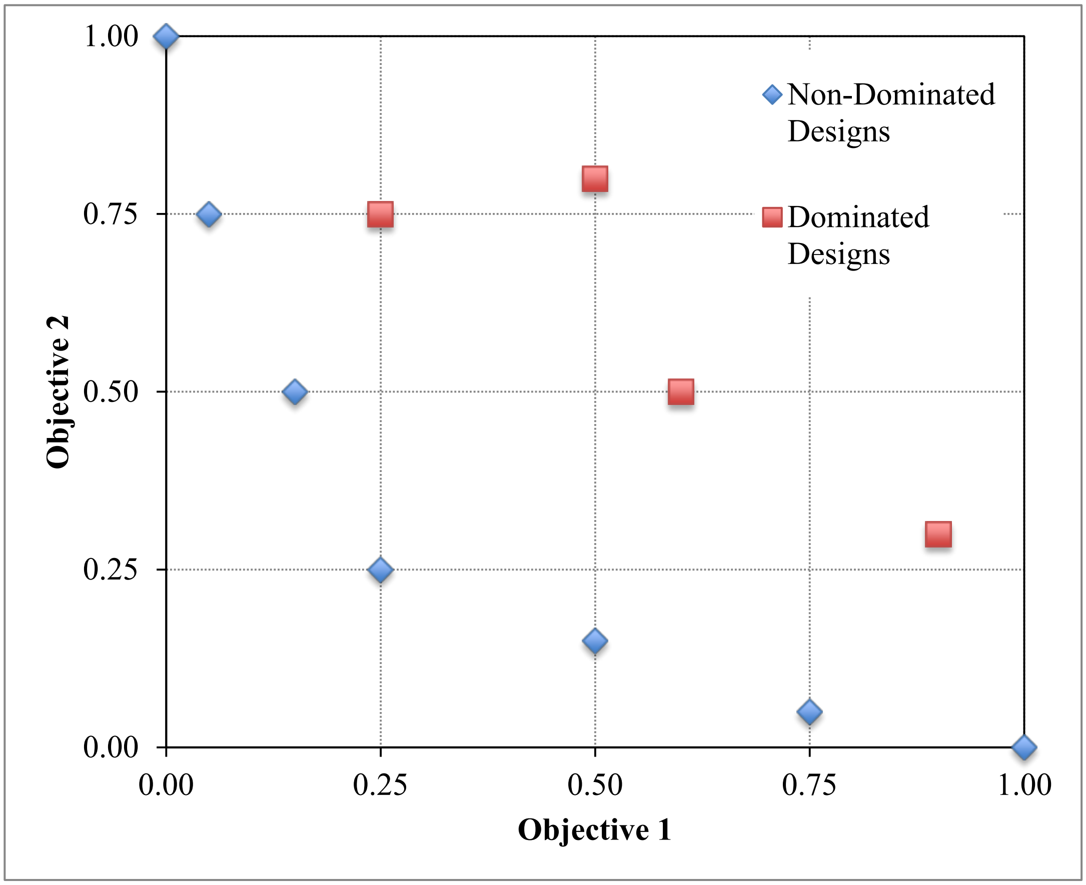


Figure 5-2: Dominated and non-dominated designs

Equation 5-1 is equivalent to

$$\min_k\left(\mathrm{f}_k^i - \mathrm{f}_k^j\right) \geq 0 \tag{5-2}$$

Thus, design *i* is a dominated design if

$$\max_{j \neq i}\left(\min_k\left(\mathrm{f}_k^i - \mathrm{f}_k^j\right)\right) \geq 0. \tag{5-3}$$

The maximin fitness of design *i* is

$$\max_{j \neq i}\left(\min_k\left(\mathrm{f}_k^i - \mathrm{f}_k^j\right)\right). \tag{5-4}$$

The maximin fitness of non-dominated designs will be less than zero, and the maximin fitness of dominated designs will be greater than or equal to zero. Therefore, the fittest designs have the lowest maximin fitness value. Not all non-dominated designs have the same value of maximin fitness. Some have more negative values than others. Those with the most negative values are the most diverse (isolated from other designs in objective space). Thus, the maximin fitness function rewards both dominance and diversity.

5.3 New Generations

Each generation of chromosomes becomes the chromosome pool for the next generation of chromosomes. Genetic algorithm reproduction models genetic reproduction and includes parent selection, crossover, and mutation.

5.3.1 Parent Selection

Parent selection is simultaneously random and fitness-based. The type of selection used in this model is called “tournament selection.” First, a specified number of the chromosomes from the previous generation are randomly selected as part of a “tournament.” The fittest among those becomes the first parent. A second similarly sized group of chromosomes is randomly selected and the fittest among them becomes the second parent.

5.3.2 Crossover

The two parents produce two children in a process called crossover. The crossover method for the skybridge and elevator genes is known as uniform crossover (Srinivas and Patnaik 1994). For each of these genes, a coin is flipped. If it is heads, the first child gets the first parent's gene, and the second child gets the second parent's gene. If it is tails, the opposite assignment is made. Children therefore get approximately 50% of their genes from the first parent and 50% of their genes from the second parent.

The crossover method for the space use genes is slightly different. Bookkeeping is again required to insure feasibility. As in the creation of the starting population, the numbers of slots available for each space use are monitored, initialized with the values in Table 3-2. For each space use gene in the chromosome, a coin is flipped. If it is heads, the record is checked. If the first child can add a gene for the space use type specified in the first parent's chromosome, that space use type is assigned. If the second child can add a gene for the space use type specified in the second parent's chromosome, that space use type is assigned to the second child. If the flipped coin is tails, the opposite assignment is attempted. In all of the cases, if the space use type specified by the parent gene is not available to be added to the child, a random available space use type is chosen and the type is assigned. After each assignment, the record is updated. To avoid randomly generating the same section of the chromosome during space use crossover, the space use designs are considered in random order, just as in the starting generation.

5.3.3 Mutation

Chromosome mutation takes place after the crossover step to further introduce variation into the designs. For each gene in the chromosome, a random number is generated. If that number is less than a specified threshold, mutation proceeds, otherwise the gene is not mutated. Genes are mutated according to the following process. If it is a skybridge or an elevator gene, the gene is randomly assigned a new value in its range (0 to 1 for skybridges and 1 to 3 for elevators). If it is a space use gene, another space use gene is randomly selected and the two space use types are swapped.

5.4 Elitism

After each chromosome is created, its fitness is evaluated using the values of the objective functions from Chapter 4 and the maximin fitness function. The old and new chromosomes are then ranked according to fitness, and the fittest of the chromosomes survive to create a new generation.

5.5 Optimization Summary

As discussed in this chapter, the genetic algorithm proceeds through the creation, evaluation, selection, crossover, mutation, and elitism phases. Repetitions of this cycle are called generations. The genetic algorithm runs for hundreds of generations until optimal designs are found. Unique approaches to creation and crossover ensure feasibility of all chromosomes for all generations. And elitism and the maximin fitness function ensure that non-dominated and diverse chromosomes perpetuate till the last generation. The chromosomes surviving after the last generation represent the fittest designs discovered during the search.

6 RESULTS

The genetic algorithm runs for a large number of iterations in order to find the best non-dominated models. Unfortunately, the algorithm can tend to focus on only a relatively small set of the millions of available designs. To introduce diversity into the search, the larger search can be broken into smaller searches wherein specific gene values are fixed. This chapter explains the search process for both the smaller and the larger searches and reports the results of these searches.

6.1 Seed Designs

In this thesis, the larger search was broken into four smaller searches. These searches are called seed design searches because the best design discovered in each of these searches is used as input for the full search and is called a seed design. The skybridge and elevator gene values were fixed for each seed design search. These fixed values are shown in Table 6-1.

Table 6-1: Fixed Gene Values In Seed Design Searches

Search	Skybridge Genes	Elevator Genes
1	1	3
2	0	3
3	1	1
4	0	1

With these values fixed, the only design variation during each of these seed design searches was the arrangement of the space uses. All of the searches in this thesis ran using the parameters in Table 6-2. Numerous tests showed these parameters to be most effective for finding optimal designs using the described greenplex model.

Table 6-2: Genetic Algorithm Parameters for Series 1-4

Parameter	Value
Number of Generations	250
Generation Size	200
Tournament Size	10
Crossover Probability	0.5
Mutation Probability	0.01

To discover the seed designs, each of the four seed design searches was broken down into a series of seven smaller searches. In the first four rounds of the series, the searches ran for 250 generations. The first round consisted of sixteen simultaneous algorithm executions, four executions each for the four configurations in Table 6-1. Multiple executions of the same search generate different arrangements because the random number generator is initialized using the system clock. The single best design resulting from each of the four groups was retained and grouped with the four best designs discovered during all previous model test runs (one for each configuration). These eight best designs were used as input for the second round of searches. Such input is valid because any prior results only represent another way to configure the greenplex space uses and all could be found with enough searches. Also, prior designs are used only as a small subset of the initial designs for each round of seed design searches, and better designs are subsequently found. These eight seed designs were therefore part of the initial set of chromosomes for four new seed design searches using the parameters in Table 6-1. In the second round, only four searches were run, one for each of the configurations shown in the table.

Following round two, the four new best designs (one from each configuration) were retained and used as input for the round-three searches. The round-three best designs were then used as input for the round-four search.

The process was somewhat different for rounds five, six, and seven. The round-four best designs were nearly optimal for each of the four configurations. The next three rounds ran according to the parameters in Table 6-3 to see if those four best designs could be refined further. Mutation was set as the only form of chromosome modification, to keep changes slight. Also, since diversity in the starting generation is not beneficial to a mutation-only search, the input generation was populated entirely with 200 identical chromosomes: 200 copies of the best design from each of the respective seed design searches in round four. In other words, input for the configuration 1 search in round five was 200 copies of the best configuration 1 design found in round four, and so forth.

Table 6-3: Genetic Algorithm Parameters for Series 5-7

Parameter	Value
Number of Generations	250
Generation Size	200
Tournament Size	2
Crossover Probability	0.0
Mutation Probability	0.01

The best designs found in round five were used for input into round six, and the best designs found in round six were used for input into round seven. After seven rounds, no travel time objective had changed more than 0.0003 points in the last three rounds, so the search was terminated.

The following sections discuss the results of the four seed design searches. Each section will include details regarding the search proceedings and the seed design discovered. Specifically, the travel times and trip distributions associated with each seed design, and the trends observed by analyzing the space use for each design will be discussed. For simplicity, the best designs discovered in the four searches are called “seed 1,” “seed 2,” “seed 3,” and “seed 4.”

6.1.1 Seed 1 – Maximum Number of Skybridges and Maximum Number of Elevators

The values for the travel time objective function (see 4.1) at the end of each round of the seed 1 search are shown in Table 6-4. These and all other travel time objective function values in the seed design searches have been divided by 525s to normalize the results.

Table 6-4: Best Objective Values After Each Round of Seed Design Search 1

Round Number	Objective Function Value
1	0.333789
2	0.326553
3	0.323227
4	0.321595
5	0.321391
6	0.321333
7	0.321152

The search progression for the seed 1 search is shown in Figure 6-1. The jumps in the average fitness value occur at the start of a new round, specifically rounds 2, 3, and 4.

Seed 1 has a travel time objective value of 0.321152. With a total of 7,280 trips being made in the model and a 525s normalization, this corresponds to a total travel time of 1,227,443 seconds and an average travel time of 168.6 seconds or 2.810 minutes. This is the fastest average of all of the executions run during all searches in this thesis. Such a result is expected, as this seed design search has the greatest number of skybridges and elevators and the most likelihood for uncongested links.

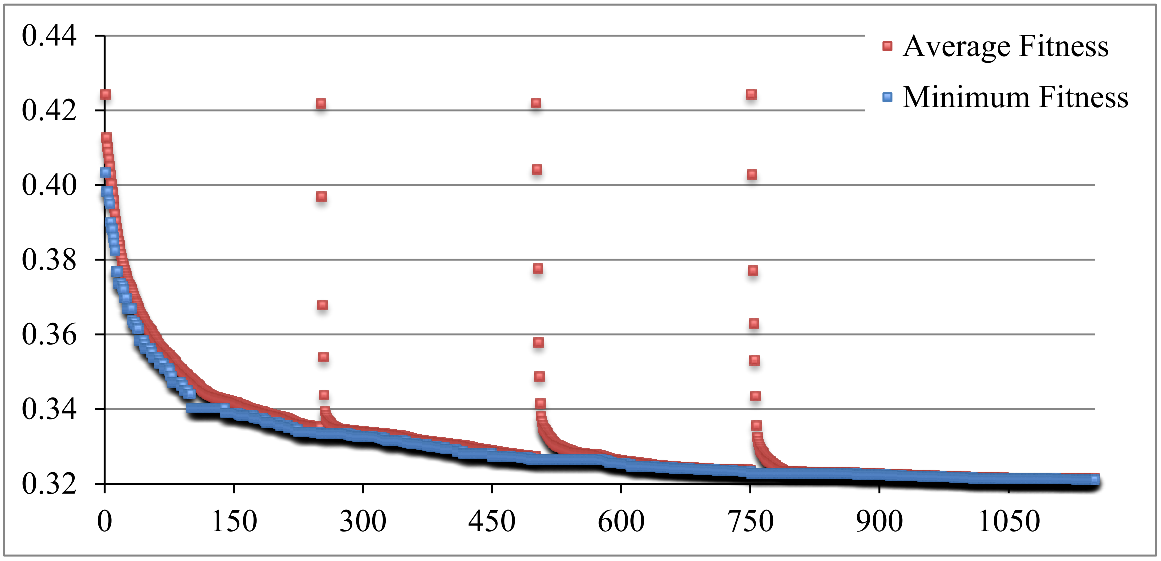
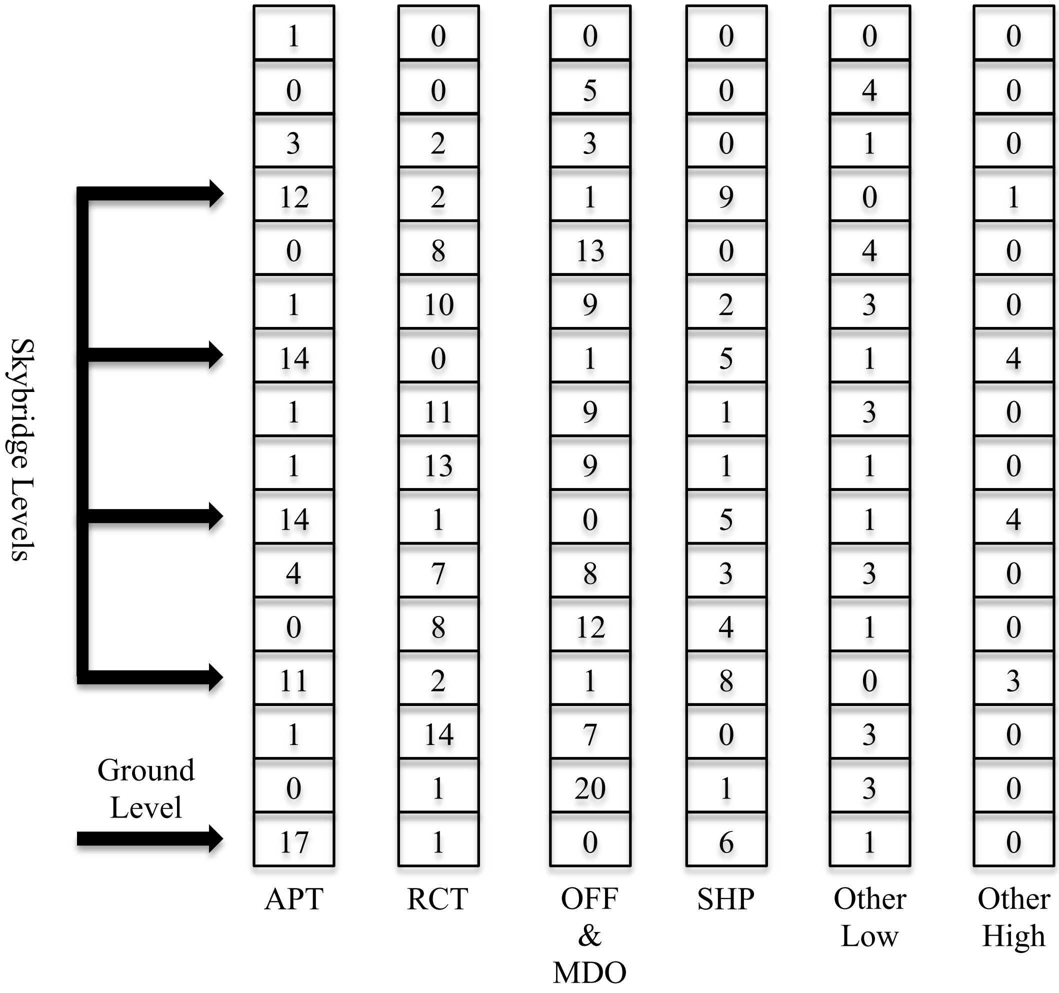


Figure 6-1: Search progression for seed 1.

The space use arrangement of seed 1 is interesting. Figure 6-2 shows six columns of numbers. These columns contain the total number of each type of space use appearing on the corresponding three-floor level of the entire seed 1 greenplex. Apartment (APT), Condominium (RCT), and Shopping Center (SHP) land uses have unique trends and are shown in independent columns. The General Office (OFF) and Medical-Dental Office (MDO) trends are similar and are therefore grouped into one column. Other low-volume generators (lower than 600 trips attracted) are shown in another column, and high-volume generators (more than 600 trips attracted) are shown in the last column. The arrows point to the skybridge levels.



APT	RCT	OFF & MDO	SHP	Other Low	Other High
1	0	0	0	0	0
0	0	5	0	4	0
3	2	3	0	1	0
12	2	1	9	0	1
0	8	13	0	4	0
1	10	9	2	3	0
14	0	1	5	1	4
1	11	9	1	3	0
1	13	9	1	1	0
14	1	0	5	1	4
4	7	8	3	3	0
0	8	12	4	1	0
11	2	1	8	0	3
1	14	7	0	3	0
0	1	20	1	3	0
17	1	0	6	1	0

Figure 6-2: Number of each space use type per greenplex level – seed 1.

In this figure, as well as in the similar figures representing the next two seed designs, there are a few patterns. First, residences are integrated into nearly every zone level. Apartment zones, which produce a larger number of trips, are more often found on the skybridge levels, while condominium zones are more regularly found on the interior levels. Office zones and other low-volume attractions are more commonly found on the interior (non-skybridge) levels, while the high-volume attractions are nearly always found on the skybridge or ground levels. Perhaps because there are so many shopping center zones, they are found throughout the design, but they also tend to fall on the skybridge levels. These trends are more pronounced in the next two designs.

Space use trends on a building-by-building basis are interesting as well. To minimize travel times, space use is mixed within each building. Figure 6-3 shows the number of different types of space use in each building. No building has fewer than four types of space use.

4	6	6	8	5
6	7	7	6	6
5	6	6	6	8
6	6	7	6	6
7	8	7	6	7

Figure 6-3: Number of different space use types in each building – seed 1.

Just as notable as the space use distribution is the trip distribution. In this model, productions always generate a full quota of trips. This is not the case with attractions, however. As per the gravity model, the number of trips actually visiting an attraction depends both on the number of trips attracted and the travel time to get to that attraction. Though heavy attractions may be located in specific places in the model, whether they actually gather trips should depend on their relative accessibility. Figure 6-4 shows that this is indeed the case. This figure displays the percentage of all of the trips in the model that terminate at each level. In seed 1, the skybridge levels clearly get the most visits, with level 6 being the most visited overall. This indicates that level 6 is the most easily accessible level in the model.

Level 15	0%
Level 14	0%
Level 13	1%
Level 12	15%
Level 11	2%
Level 10	3%
Level 9	16%
Level 8	2%
Level 7	2%
Level 6	23%
Level 5	3%
Level 4	4%
Level 3	18%
Level 2	1%
Level 1	3%
Level 0	7%

Figure 6-4: Percent of trips visiting each level – seed 1.

6.1.2 Seed 2 – No Skybridges and Maximum Number of Elevators

The values for the travel time objective function at the end of each round of the seed 2 search are shown in Table 6-5.

Table 6-5: Best Objective Values After Each Round of Seed Design Search 2

Execution Number	Objective Function Value
1	0.390833
2	0.379858
3	0.376157
4	0.374531
5	0.374348
6	0.374240
7	0.374207

The search progression for the seed design 2 search is shown in Figure 6-5.

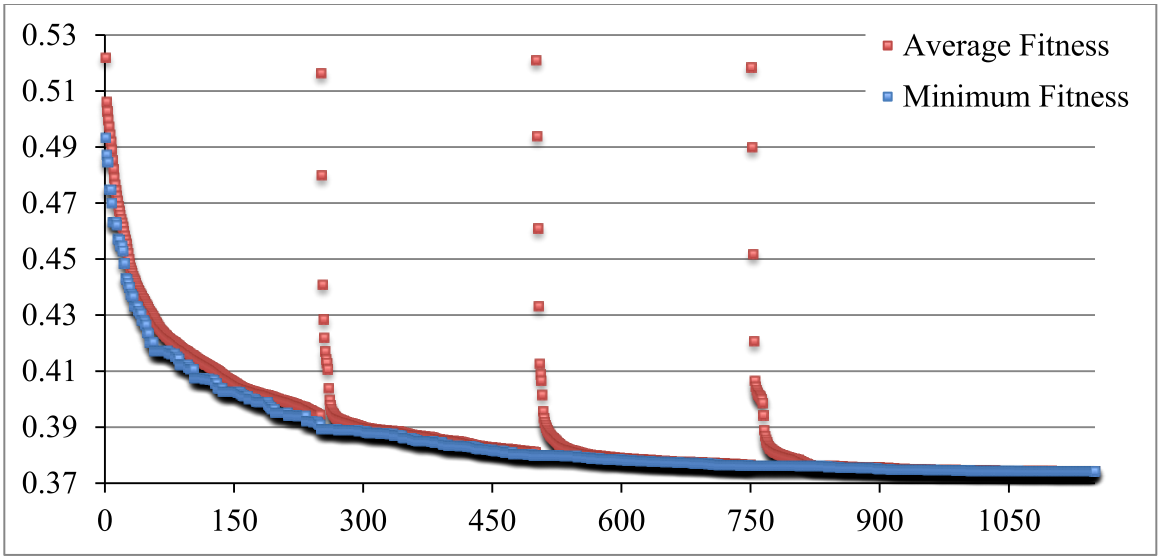
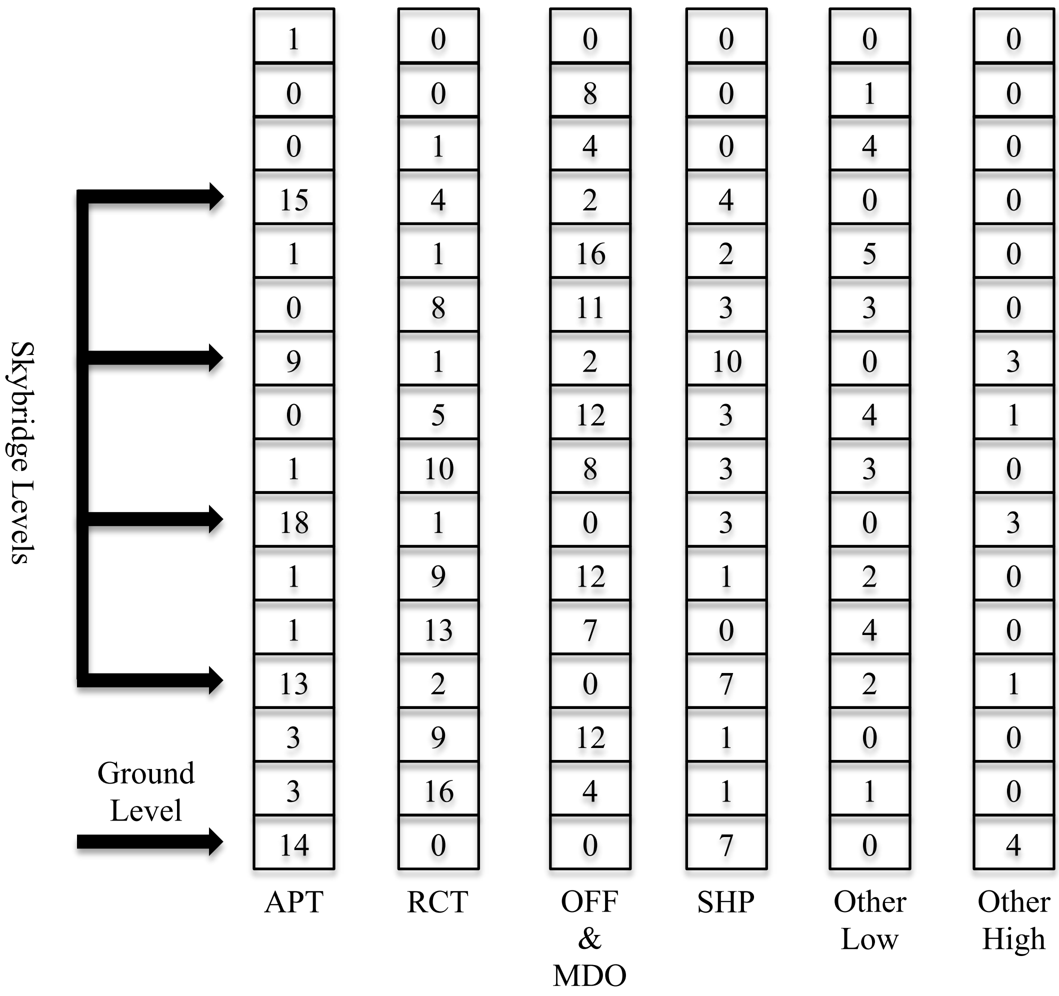


Figure 6-5: Search progression for seed 2.

As shown in Figure 6-5, the seed 2 design had a travel time objective value of 0.374207. This corresponds to a total travel time of 1,430,219 seconds and an average travel time of 196.5 seconds or 3.27 minutes. A major question asked in this thesis was whether the results for the skybridge-free design in this example would be worse than the results for the minimum elevator design in the next example. As the results in the next section show, the fittest design with skybridges and the minimum number of elevators performs better than the design without skybridges.

The space use configuration for the seed 2 design parallels the configuration for the seed 1 design. Figure 6-6 shows the level analysis, and Figure 6-7 shows the building-by-building analysis.



APT	RCT	OFF & MDO	SHP	Other Low	Other High
1	0	0	0	0	0
0	0	8	0	1	0
0	1	4	0	4	0
15	4	2	4	0	0
1	1	16	2	5	0
0	8	11	3	3	0
9	1	2	10	0	3
0	5	12	3	4	1
1	10	8	3	3	0
18	1	0	3	0	3
1	9	12	1	2	0
1	13	7	0	4	0
13	2	0	7	2	1
3	9	12	1	0	0
3	16	4	1	1	0
14	0	0	7	0	4

Figure 6-6: Number of each space use type per greenplex level – seed 2.

6	7	5	4	5
6	7	7	7	7
5	7	6	7	6
7	8	7	5	5
7	5	6	5	7

Figure 6-7: Number of different space use types in each building – seed 2.

Here again, the space uses are well distributed throughout the buildings, the higher-volume zones tend toward the skybridge levels, and the lower-volume zones tend toward the interior levels.

However, the trip distribution is not the same. Trip destinations are heavily concentrated toward the lower floors, as would be expected, since without skybridges the ground floor is the most easily accessible floor in the model. Figure 6-8 illustrates this occurrence. Note that even though skybridges are absent, the skybridge floors are still busy because the express elevators stop at these floors.

Level 15	0%
Level 14	0%
Level 13	1%
Level 12	6%
Level 11	3%
Level 10	3%
Level 9	19%
Level 8	4%
Level 7	3%
Level 6	10%
Level 5	2%
Level 4	1%
Level 3	16%
Level 2	3%
Level 1	2%
Level 0	27%

Figure 6-8: Percent of trips visiting each level – seed 2.

6.1.3 Seed 3 – Maximum Number of Skybridges and Minimum Number of Elevators

The values for the travel time objective function at the end of each round of the seed 3 search are shown in Table 6-6.

Table 6-6: Best Objective Values After Each Round of Seed Design Search 3

Round Number	Objective Function Value
1	0.334946
2	0.328469
3	0.323292
4	0.322122
5	0.321966
6	0.321640
7	0.321547

The search progression for the seed 3 search is shown in Figure 6-9.

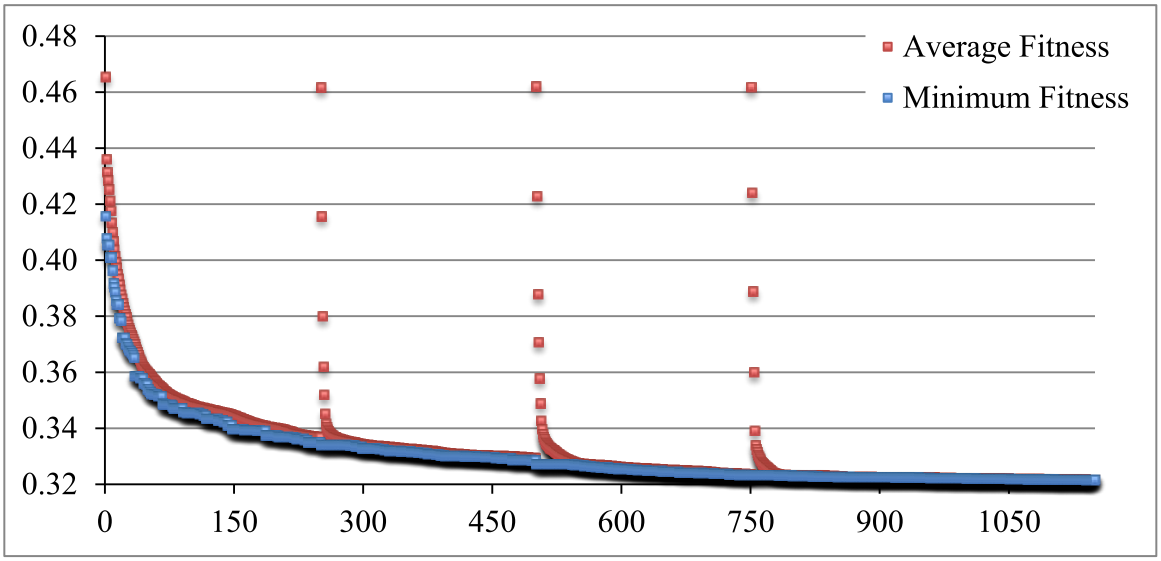
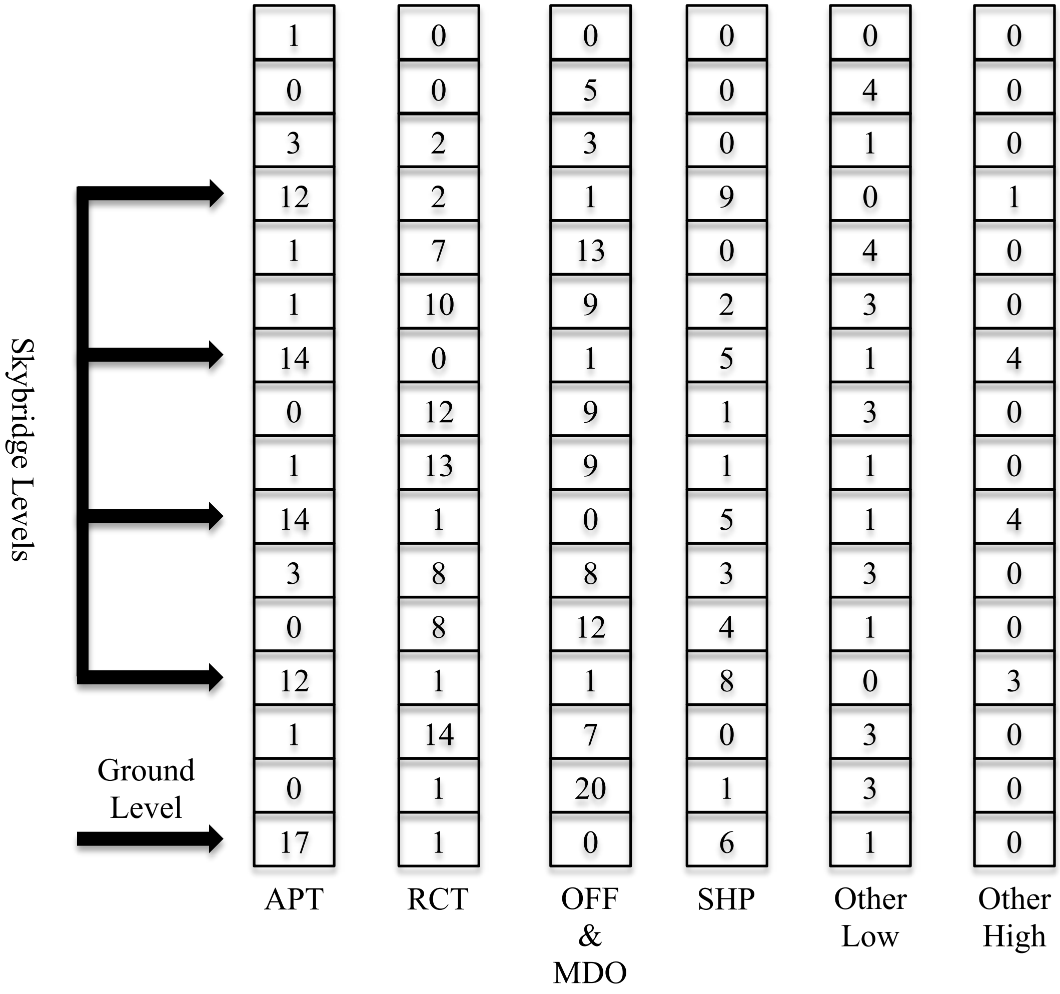


Figure 6-9: Search progression for seed 3.

The seed 3 design had a travel time objective value of 0.321547. This corresponds to a total travel time of 1,228,953 seconds, and an average travel time of 169 seconds or 2.814 minutes. These results are only minutely different from the results in the seed 1 search, suggesting that skybridge travel makes a difference in city transportation. They are certainly better than the results for seed 2, suggesting that skybridges are more effective at reducing travel time than are additional elevators.

As with the previous two searches, space use is well mixed within the buildings, higher-volume zones tend toward the skybridge levels, and lower-volume zones tend toward the interior levels. The level-by-level distribution is shown in Figure 6-10, and the building-by-building analysis is shown in Figure 6-11.



APT	RCT	OFF & MDO	SHP	Other Low	Other High
1	0	0	0	0	0
0	0	5	0	4	0
3	2	3	0	1	0
12	2	1	9	0	1
1	7	13	0	4	0
1	10	9	2	3	0
14	0	1	5	1	4
0	12	9	1	3	0
1	13	9	1	1	0
14	1	0	5	1	4
3	8	8	3	3	0
0	8	12	4	1	0
12	1	1	8	0	3
1	14	7	0	3	0
0	1	20	1	3	0
17	1	0	6	1	0

Figure 6-10: Number of each space use type per greenplex level – seed 3.

4	6	6	8	5
6	7	7	6	6
5	6	6	6	8
6	6	6	6	6
7	8	7	6	7

Figure 6-11: Number of different space use types in each building – seed 3.

A close inspection of these last two figures reveals that they are nearly identical to Figures 6-2 and 6-3. During the early rounds of the seed design searches, the optimal space use arrangement discovered by the seed 1 search often also worked best for the seed 3 parameters, and vice versa. The models diverged slightly after the mutation-only phase began, and the final designs are optimal for the respective seeds. However, the similarities are still quite apparent.

The trip distribution trends seen in seed 3 also mirror those of seed 1. In fact, the percentages shown in Figure 6-4 are exactly the same as the percentages for seed 3. This suggests that the minimum number of elevators provided in the model is adequate if skybridges are present.

6.1.4 Seed 4 – No Skybridges and Minimum Number of Elevators

The values for the travel time objective function at the end of each round of the seed 4 search are shown in Table 6-7.

Table 6-7: Best Objective Values After Each Round of Seed Design Search 4

Round Number	Objective Function Value
1	0.555276
2	0.537644
3	0.529389
4	0.511079
5	0.509945
6	0.509896
7	0.509500

The search progression for the seed 4 search is shown in Figure 6-12.

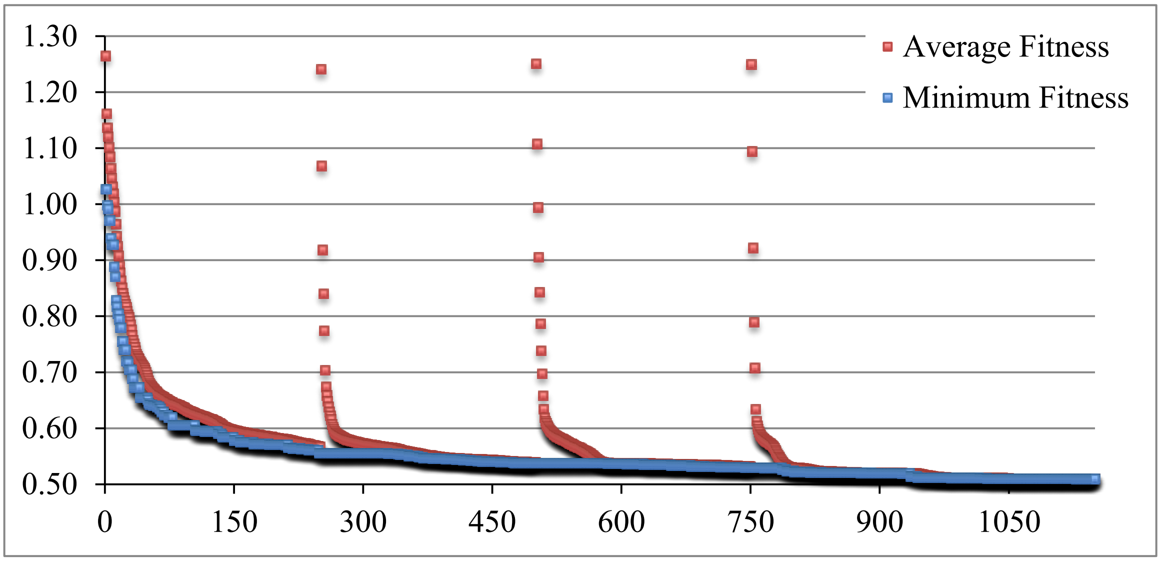
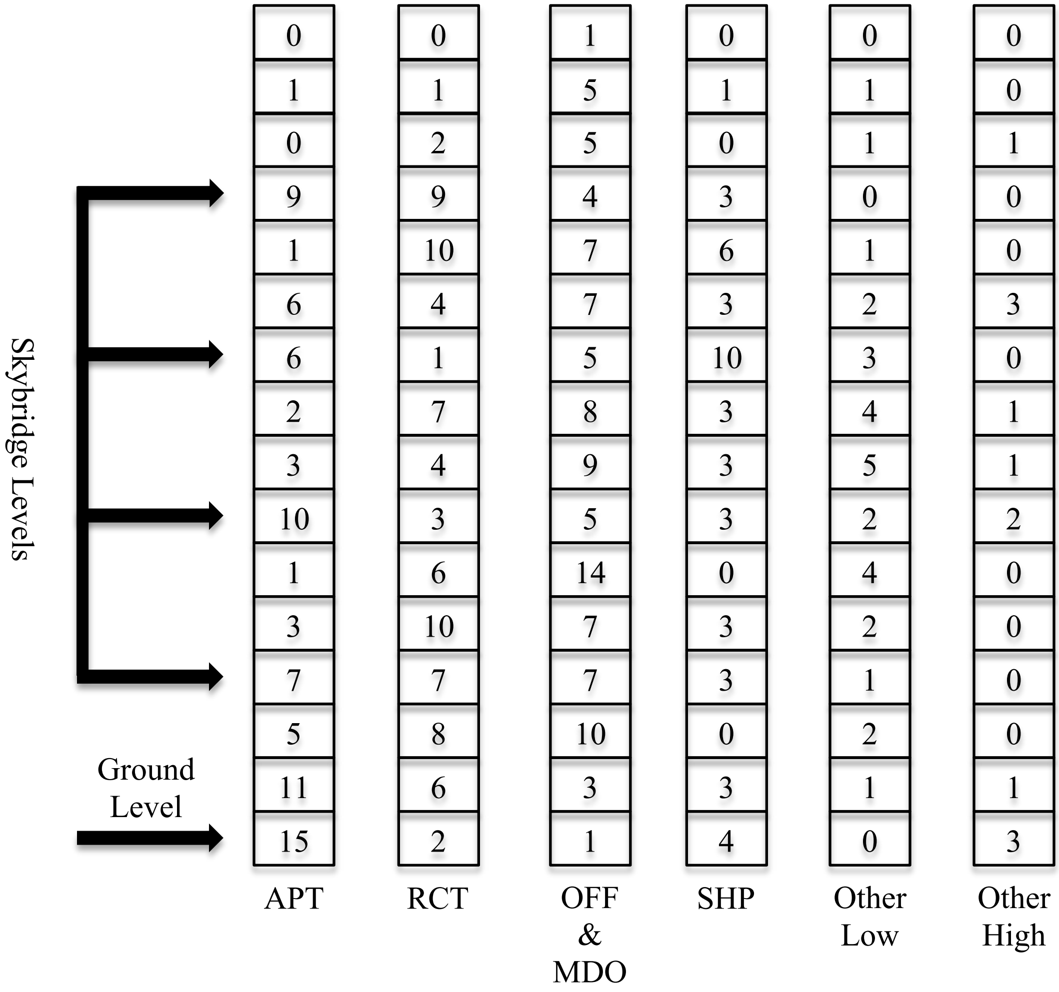


Figure 6-12: Search progression for seed 4.

The seed 4 design had a travel time objective value of 0.5095, a total travel time of 1,947,309 seconds, and an average travel time of 267 seconds or 4.46 minutes. This is markedly different from the values discovered in the previous three searches. This implies that without skybridges, the minimum number of elevators is insufficient for great travel time in a greenplex.

The space use arrangement specified in this seed design is also remarkably different. Figure 6-13 shows the new arrangement.



APT	RCT	OFF & MDO	SHP	Other Low	Other High
0	0	1	0	0	0
1	1	5	1	1	0
0	2	5	0	1	1
9	9	4	3	0	0
1	10	7	6	1	0
6	4	7	3	2	3
6	1	5	10	3	0
2	7	8	3	4	1
3	4	9	3	5	1
10	3	5	3	2	2
1	6	14	0	4	0
3	10	7	3	2	0
7	7	7	3	1	0
5	8	10	0	2	0
11	6	3	3	1	1
15	2	1	4	0	3

Figure 6-13: Number of each space use type per greenplex level – seed 4.

The productions now gravitate toward the lower levels, while offices have been moved to the higher ones. The other land uses are somewhat scattered vertically, but the largest attractor, the fast food restaurant zone, is located on the ground floor near the center of the greenplex.

The mixed-use trend in the building-by-building analysis is still apparent, as shown in Figure 6-14.

6	5	5	5	6
6	6	8	8	6
6	7	7	6	6
6	6	6	7	6
6	7	6	6	6

Figure 6-14: Number of different space use types in each building – seed 4.

Trips themselves are also more evenly distributed in seed 4. Figure 6-15 shows that the highest concentration of trip ends in this design (21%) is less than the highest concentration of trip ends in seed 2 (27%). This is despite the fact that the destination level is the same.

Level 15	0%
Level 14	1%
Level 13	2%
Level 12	5%
Level 11	5%
Level 10	5%
Level 9	18%
Level 8	4%
Level 7	5%
Level 6	11%
Level 5	4%
Level 4	4%
Level 3	8%
Level 2	2%
Level 1	5%
Level 0	21%

Figure 6-15: Percent of trips visiting each level – seed 4.

The three foregoing figures indicate that in an optimal space use design for a city with fewer elevators and no skybridges, the space uses will be well mixed. If several types of productions and attractions are found in each building, trips can be somewhat local within the individual buildings. Travel to the ground floor and other buildings will then be less necessary, improving travel times.

6.1.5 Further Comparisons

A visual comparison of the space use distribution can offer additional insight. Several of the levels in the first three seed designs look similar to the level plans shown in the following figures. Figure 6-16 shows a skybridge level (level 6) from seed design 1. Note that all of the space uses are residences (which are primarily apartments (APT)) and high-volume attractions (shopping centers, restaurants, markets, and athletic complexes). Contrast this image with the one shown in Figure 6-17. This is also a level from seed design 1, but it is an interior level (level 4). The space uses are all residences (primarily condominiums (RCT)) and low-volume attractions (offices, schools, and churches). This contrast is typical of the space use distribution throughout seed designs 1, 2, and 3.

The space use in seed design 4 follows a similar trend, with some marked differences. First, note the similarities between Figures 6-16 and 6-18, and between Figures 6-17 and 6-19. The main difference between the sets of figures is their position. While Figures 6-16 and 6-17 are from skybridge and non-skybridge floors, respectively, Figures 6-18 and 6-19 are from lower and upper floors. It seems the same trends exist, but in different places, in an optimized model.

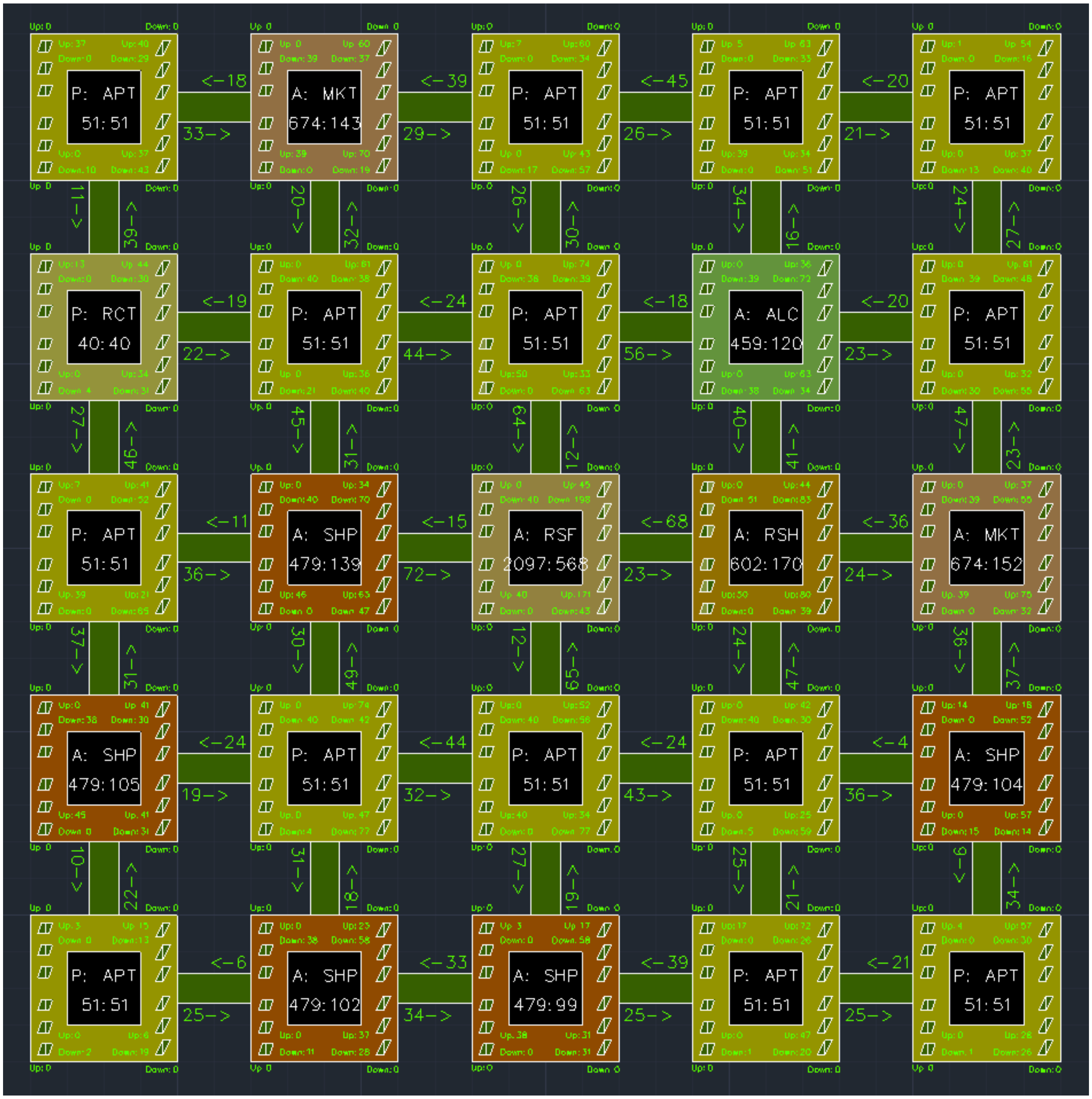


Figure 6-16: Plan view of a skybridge level (level 6) in seed design 1.

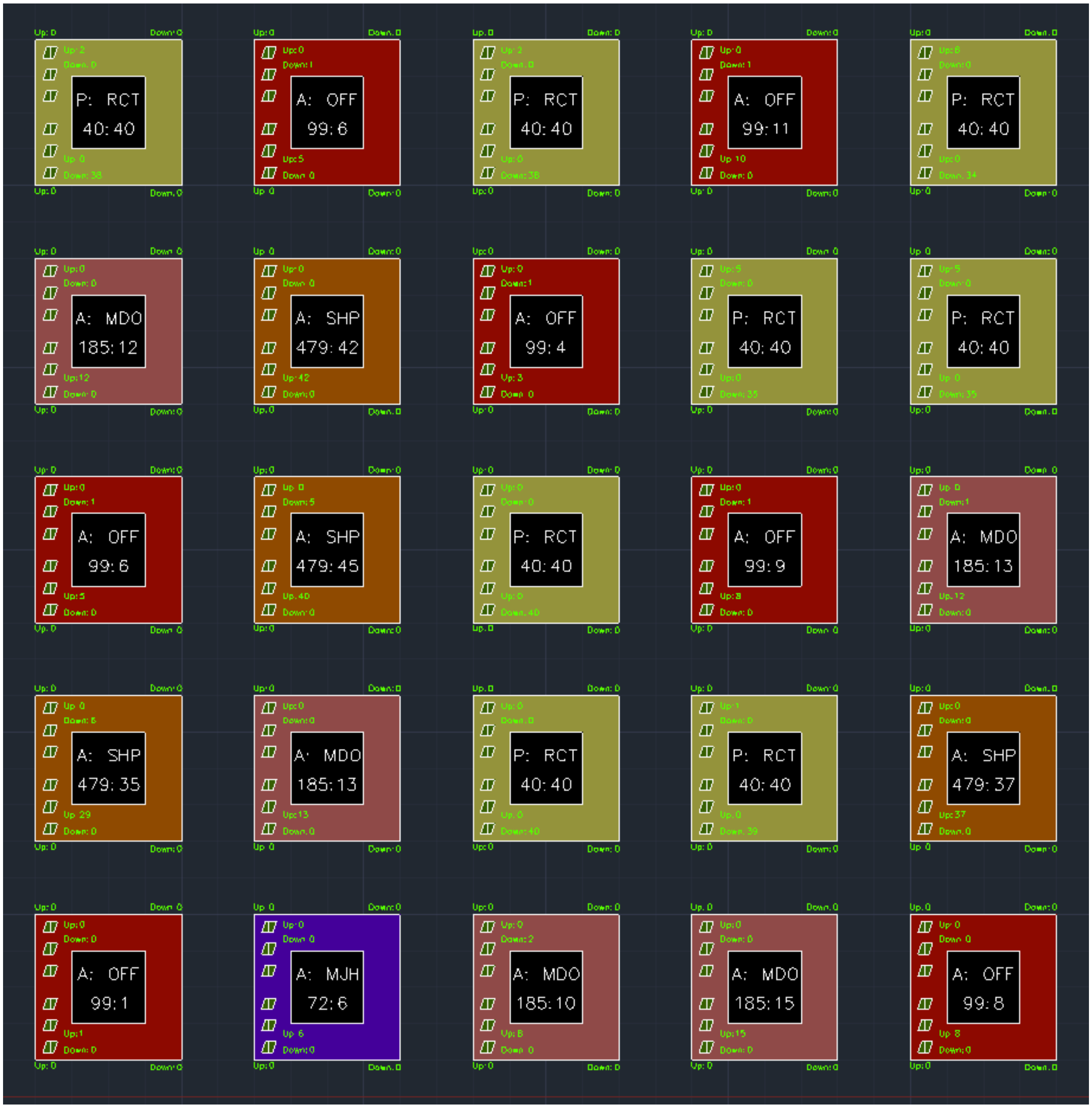


Figure 6-17: Plan view of an interior level (level 4) in seed design 1.

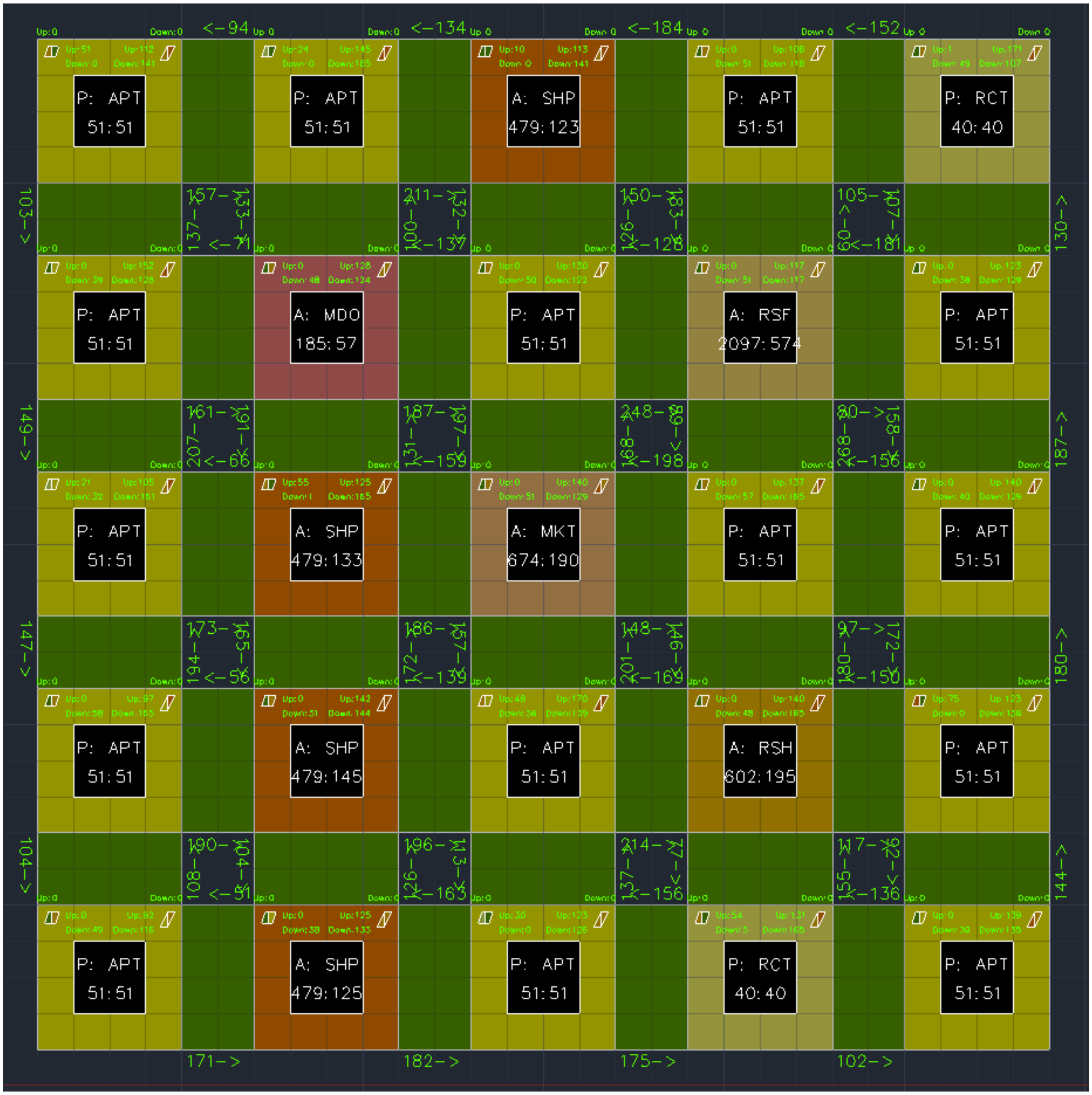


Figure 6-18: Plan view of a lower level (ground level) in seed design 4.

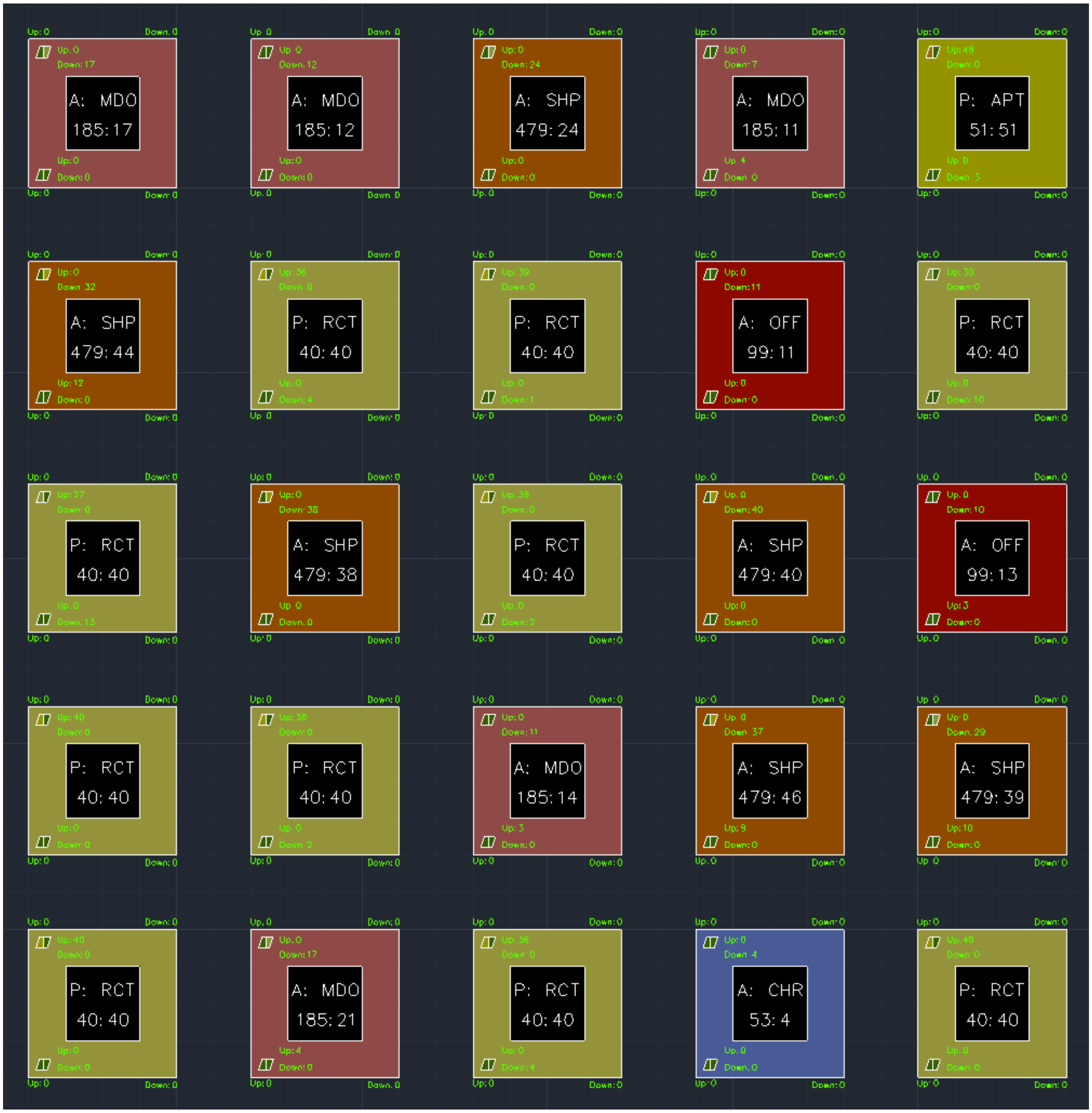


Figure 6-19: Plan view of an upper level (level 11) in seed design 4.

One more comparison merits attention. The longest trip times from each of the four seeds are shown in Table 6-8. The numbers agree with expectations. Seed 4 should show the longest trip time, because its transportation network is sparse. The seed 2 longest trip takes almost two minutes longer than the seed 3 or seed 1 longest trip, presumably because it requires a trip to the ground floor, across the somewhat congested streets, and back up again. These results are expected. The seed 3 longest trip time compared with the seed 1 longest trip time is also not surprising, particularly since the seed 1 and seed 3 designs are so similar.

Table 6-8: Longest Trip Times

Seed Number	Trip Time (s)	Trip Time (min)
1	594.198	9.9
2	706.199	11.8
3	594.198	9.9
4	1390.34	23.2

6.2 Full Search

The four seed designs obtained from the previous smaller searches were used as input for the full search. In the full search, no design variables were fixed. There were four executions of this full search. Graphical results for each search are displayed in Figures 6-20 through 6-23. Each of these figures shows 200 points representing the objective function values of non-dominated, maximally diverse designs discovered by the full search. The seed designs are shown in the plots in red. All other designs are blue. It is impossible to choose, based only on the information presented in this thesis, which of the designs in any of the four runs is the best. Each design excels in some way over the other results in its search. The information is useful, however, in identifying those designs that are optimal so that when travel time, energy use, and light penetration preferences are known, a non-dominated design may be chosen.

To better understand the usefulness of the results obtained in the full search, consider Figures 6-24 through 6-26. In these figures, the points representing both the starting generation (green) and output generation (blue) for full search 1 are shown.

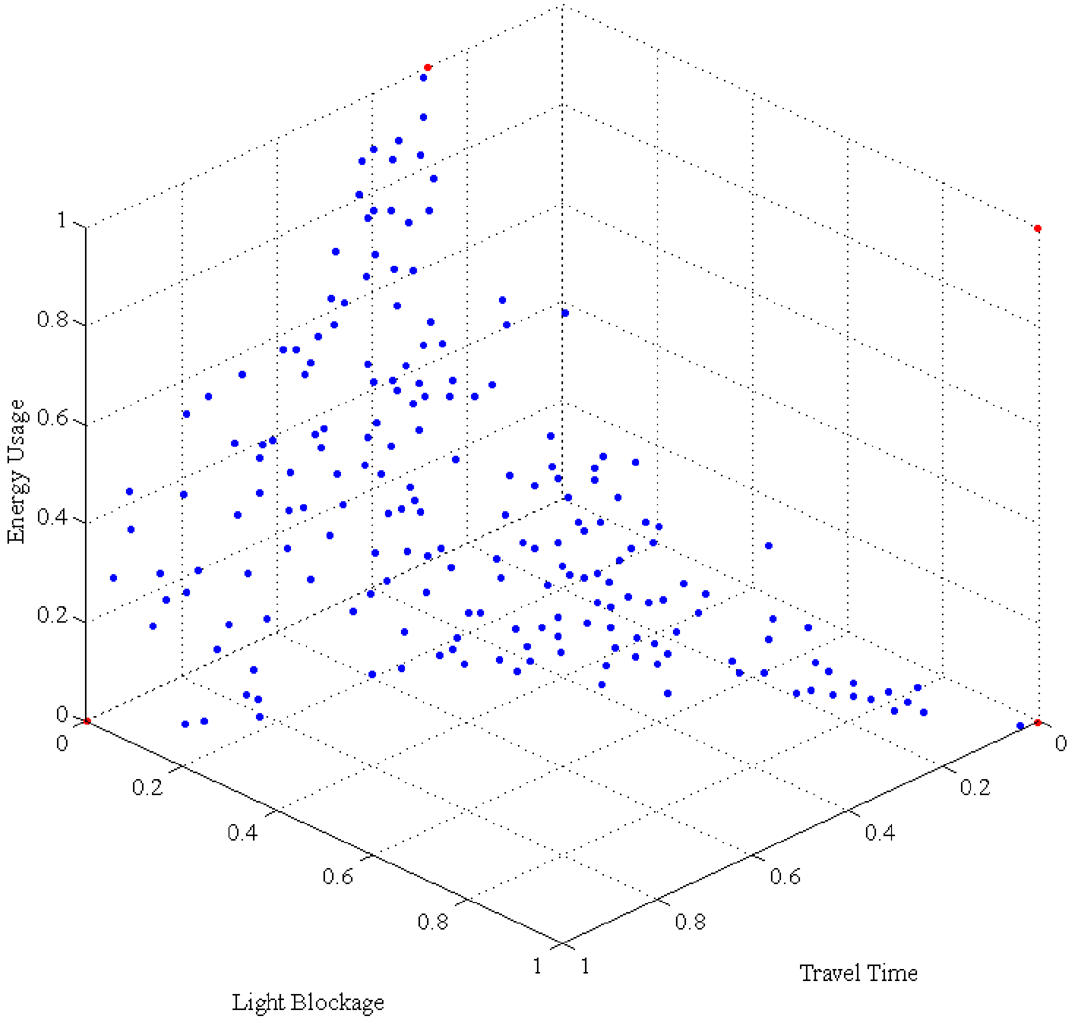


Figure 6-20: Three-dimensional plot of the objective function values – full search 1.

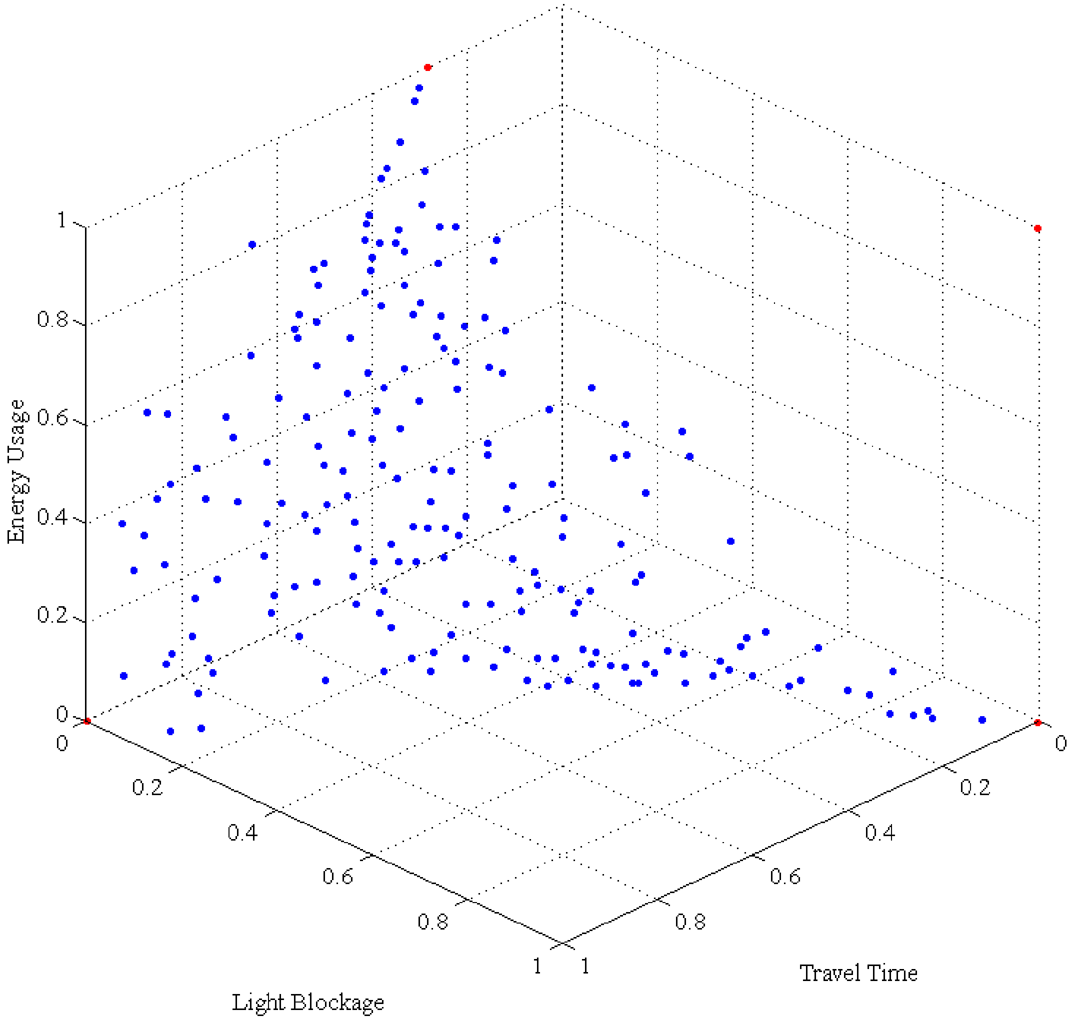


Figure 6-21: Three-dimensional plot of the objective function values – full search 2.

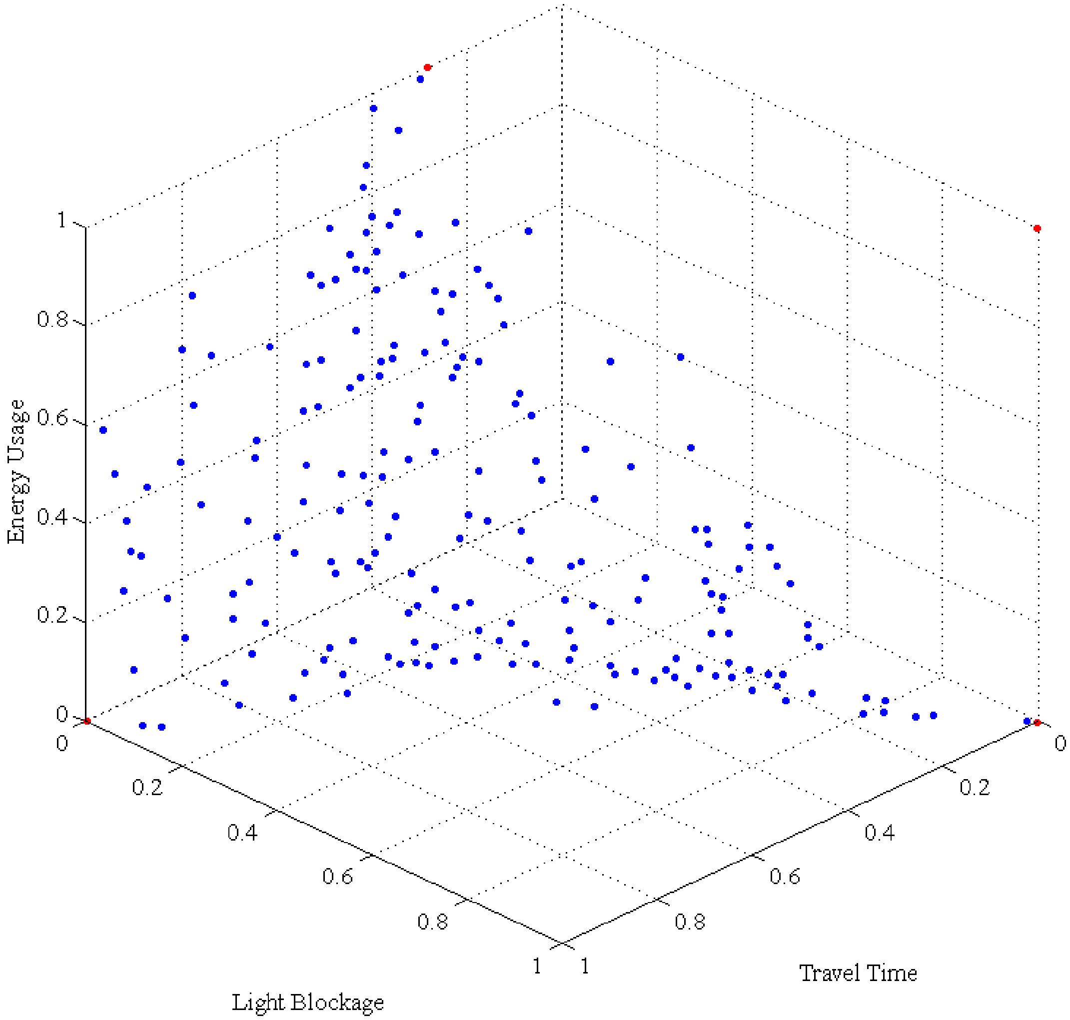


Figure 6-22: Three-dimensional plot of the objective function values – full search 3.

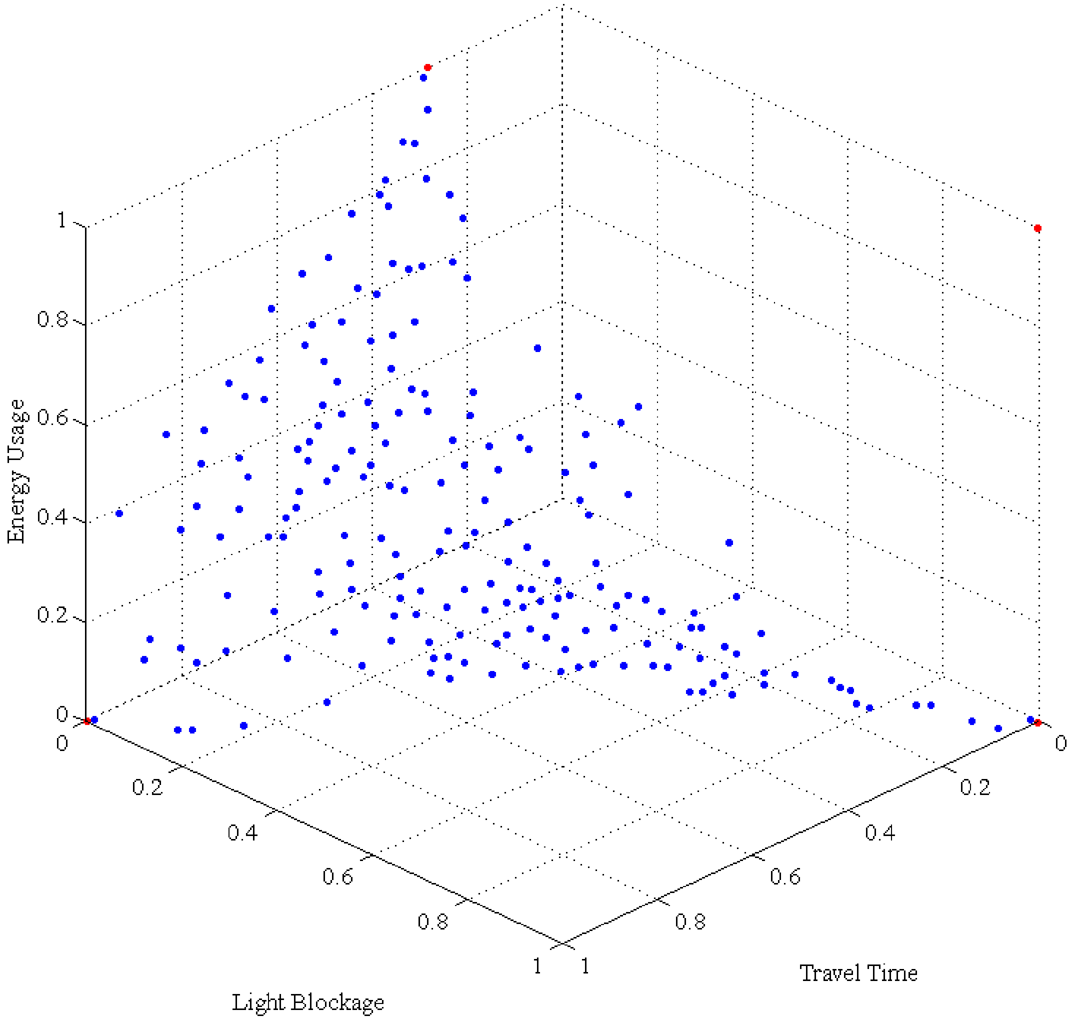


Figure 6-23: Three-dimensional plot of the objective function values – full search 4.

Figure 6-24 shows a plot similar to the ones in Figures 6-20 through 6-23. To better show how the green points lie among the blue points, Figures 6-25 and 6-26 show the views when looking down the “Energy Usage” axis and the “Travel Time” axis, respectively.

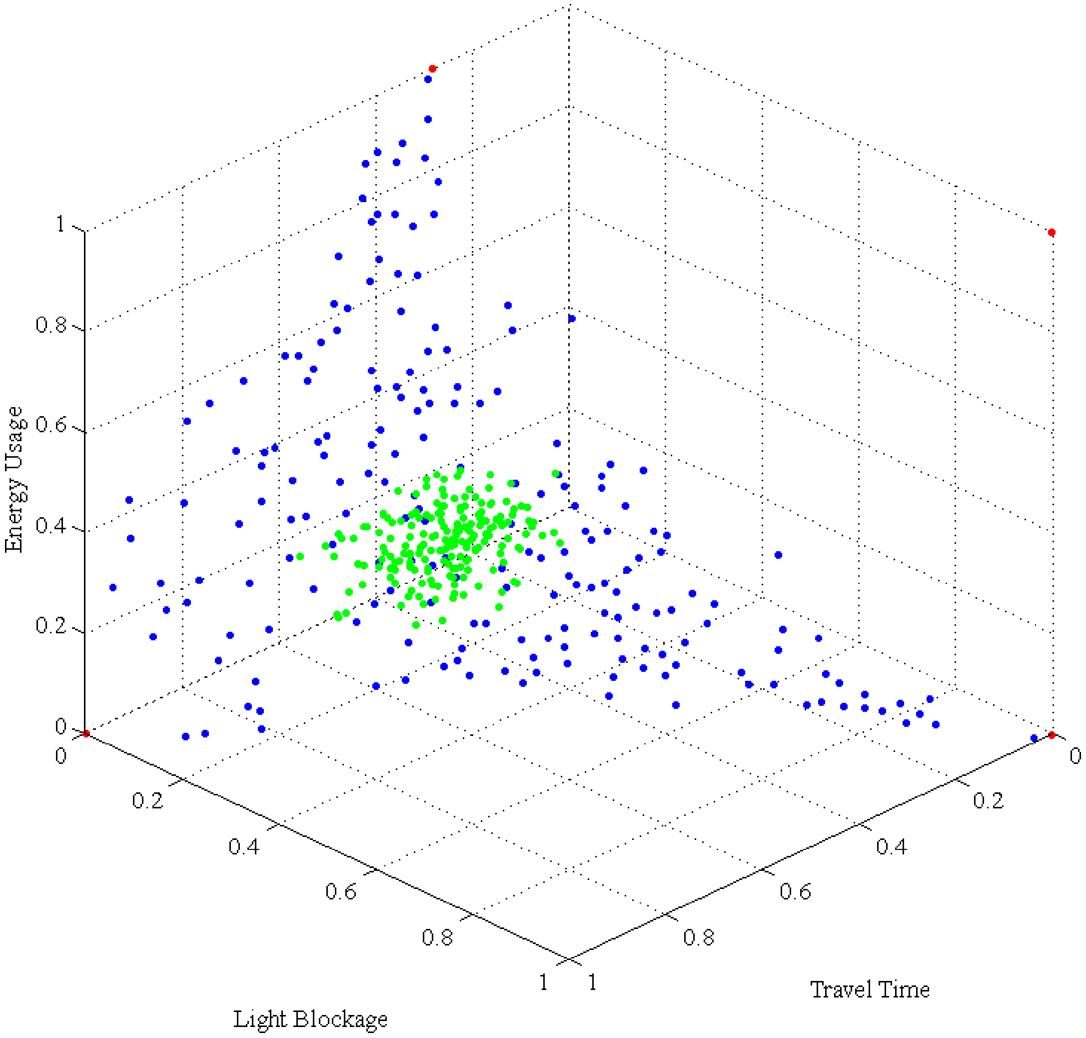


Figure 6-24: Starting and output generations on same graph – full search 1.

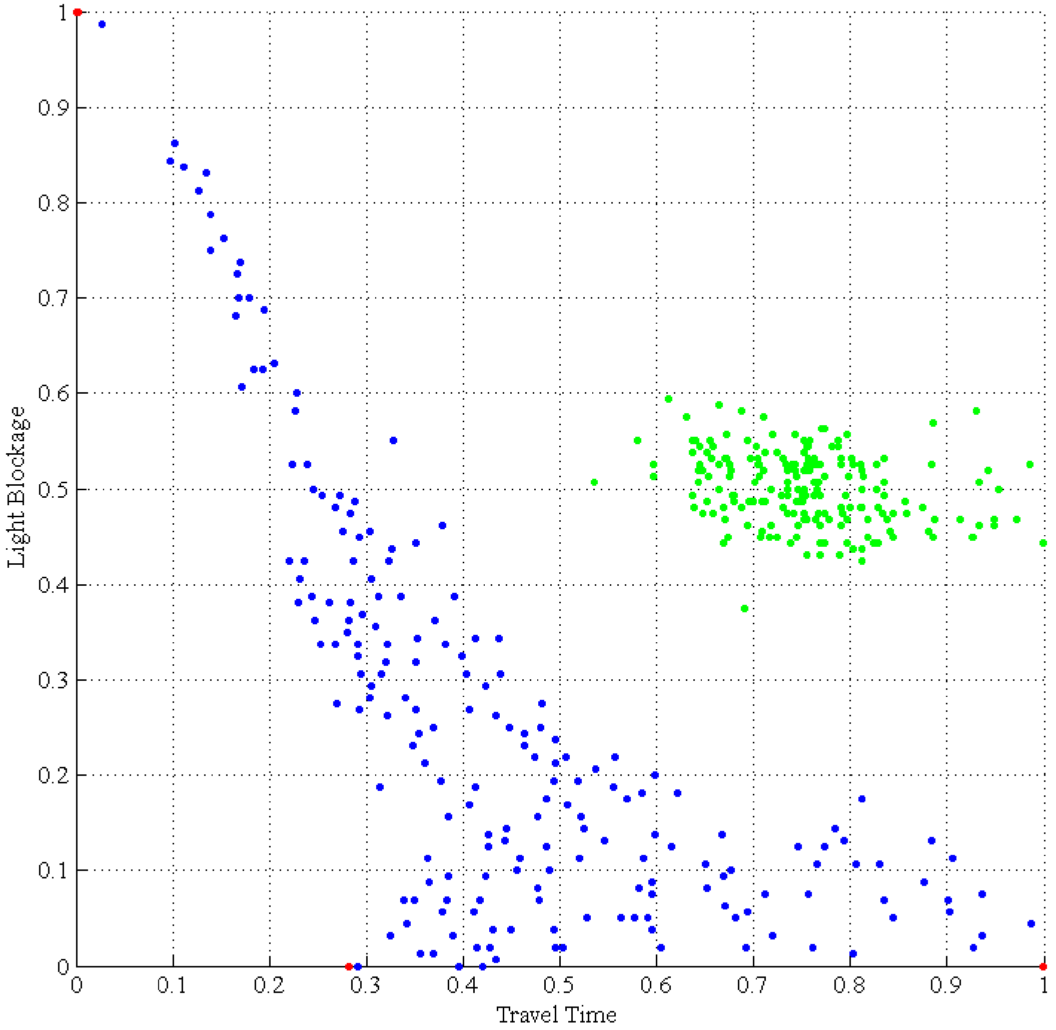


Figure 6-25: Starting and output generations on same graph – energy usage axis view.

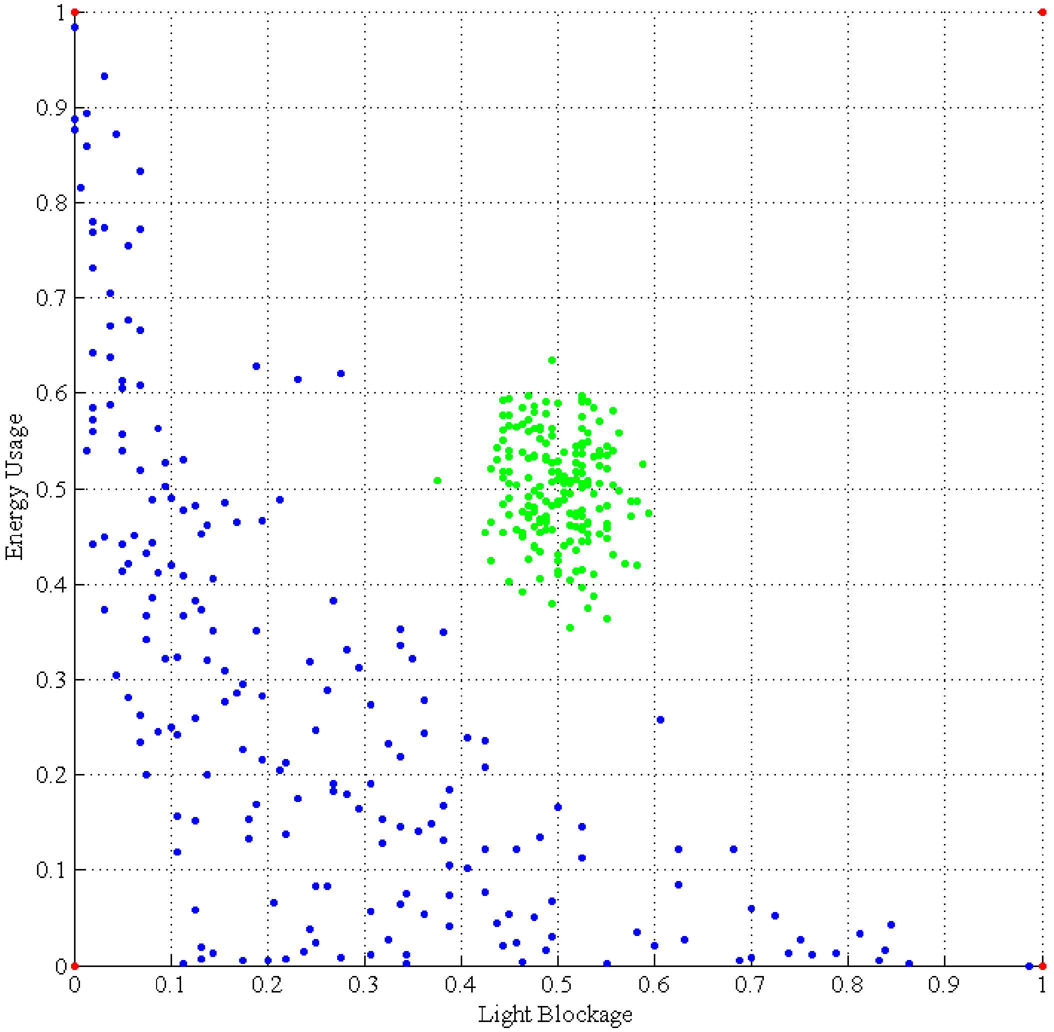


Figure 6-26: Starting and output generations on same graph – travel time axis view.

As is seen in these figures, the objective function values in the final generation are universally better than the values in the starting generation. The green designs from the starting generation are all similar, dominated designs. In contrast, the blue designs from the output generation of the full search make up a set of diverse, non-dominated designs.

The seed designs discussed in the earlier sections represent the extremes in greenplex design. The results of the full run represent compromise designs, which exhibit tradeoffs among the four seed designs. Table 6-10 shows the values of the three objective functions for the four seed designs and for a compromise design from the final generation of full search 1. Values for each objective have been normalized according to the values shown in Table 6-9.

Table 6-9: Full Search Normalization Values

Objective	Minimum Value	Maximum Value
Trip Time	168.6s	267.5s
Light Blockage	0	160
Energy Usage	4,593	13,779

Table 6-10: Objective Function Summary

Design	Trip Time	Light Blockage	Energy Usage
Seed 1	0.0000	1	1
Seed 2	0.2817	0	1
Seed 3	0.0021	1	0
Seed4	1.0000	0	0
Compromise Design	0.3147	0.1875	0.6283

Two things should be noted. First, each compromise design is a non-dominated design. No design in Table 6-10, or in the final generation of any of the four full searches is worse in every respect than any other design from that same search. Second, this model does not apply any weighting system to the three objectives, nor can the model compare the scores for the three objectives. Citizen preference, energy restrictions, etc. may create a weighting later, but the model cannot dictate these preferences.

6.3 Results Summary

The results from this research can be grouped into two categories: seed design results and full search results. The seed design results indicate that skybridges are effective in reducing travel time, and that adding skybridges can be more effective than adding elevators. The seed designs results also indicate that in tall buildings with skybridge floors or express elevator stops, space use on these levels should be reserved for higher density residential or for space uses that attract large numbers of trips. Finally, the seed design results suggest that mixed use in buildings is generally good for optimal travel times.

The full run results suggest that there are hundreds of available non-dominated designs that minimize travel time, light blockage, and energy usage in a greenplex. The report displays 1,000 of these designs. Further studies and input from other disciplines could enable one of these non-dominated designs to be selected and developed into a sustainable, walkable community.

7 CONCLUSIONS

The significant work contributions in this thesis include the following. First, a multi-objective genetic algorithm was developed for optimizing space use and transportation in a 3D walkable city. Second, using that algorithm, four seed designs were discovered that examined the extreme design cases and their effect on travel time. These four cases are cities where 1) buildings contain the maximum number of elevators and are fully-connected to their adjacent buildings with skybridges, 2) buildings contain the maximum number of elevators but are not connected with skybridges, 3) buildings contain the minimum number of elevators and are fully-connected to their adjacent buildings with skybridges, or 4) buildings contain the minimum number of elevators and are not connected with skybridges. Third, from these four designs a full search was performed that produced a diverse, non-dominated set of feasible designs. Fourth, a procedure was developed to guarantee feasibility of every design considered by the genetic algorithm.

7.1 Observations

Along with these contributions, several observations were made in this thesis that are noteworthy. The observations come from studying the seed design search results. These observations include notes on skybridge effectiveness, space use arrangement, and mixed-use benefits.

7.1.1 Skybridge Effectiveness

First, skybridges reduce travel time more than elevators do. Total travel time for the fully connected seed designs is almost identical, independent of the number of elevators. Removing the skybridges yields an immediate increase in total travel time, even if buildings have the maximum number of elevators. Adding a full 160 skybridges to the design with the maximum number of elevators resulted in a 14% reduction in total travel time, and a 16% reduction in travel time of the longest trip. Adding a full 160 skybridges to the design with the minimum number of elevators resulted in a 37% reduction in total travel time and a 57% reduction in travel time of the longest trip. Adding the maximum number of elevators to the design with the minimum number of elevators resulted in a 27% reduction in total travel time and 49% reduction in travel time of the longest trip. These measures confirm that skybridges can be more effective than elevators at reducing travel time.

7.1.2 Space Use Arrangement

Second, to minimize travel time in a city with skybridges and/or sufficient numbers of express elevators, space uses that generate many trips should be located on the skybridge levels (or express elevator stop levels), and space uses that generate fewer trips should be located on the interior levels. If skybridges are present, the productions and attractions that generate the most trips should be located toward the vertical center of the greenplex, on a skybridge floor. If skybridges are not present, these productions and attractions should be on the ground level. If sufficient express elevators are also not present, space uses should be well mixed vertically, with a general concentration of the space uses that generate the most trips toward the ground level.

7.1.3 Mixed Use Benefits

Third, mixed use reduces travel time. All four of the seed designs exhibited mixed use in the variety of space uses included in each building. The first three seed designs also showed structured mixed use on layer-by-layer basis, while the fourth design showed a benefit for slightly less structured mixed use vertically.

7.1.4 Summary

The results of this research support the introduction of multiple levels of skybridges into today's cities. The models successfully show that skybridges reduce travel time and are more effective at doing so than are extra elevators. Massively interconnecting future buildings with skybridges would effectively create a walkable environment with minimal congestion.

7.2 Further Research Recommendations

The work done in this thesis naturally invites several new research questions. First, if space use requirements and trip generation properties are defined more correctly, do the observed trends change? Second, what happens to the trends if a bigger city is studied, or if external trips are allowed? Third, what effect would a more realistic elevator model have on the results? And fourth, what are the environmental, social, and other factors that would allow a "best" choice to be made from among the non-dominated designs generated in this research? Though future greenplexes may not resemble the one studied, this work should provide the foundation necessary for studying these greater questions.

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