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Profitability versus safety of high-rise office buildings

S. Khajehpour[1] and D. E. Grierson[2]

Abstract: The paper applies a computer-based method involving stochastic search, multi-criteria optimization and color filtering to investigate the tradeoff between the life-cycle profitability of high-rise commercial office buildings and their load-path safety against progressive collapse under abnormal loading. The study was motivated by the progressive-collapse failure of the twin towers of the World Trade Center in New York on September 11, 2001. The assessment of life-cycle profitability is based on annual lease rates for office space that reflect the amounts of open floor area and natural window lighting that a building has. The assessment of load-path safety against progressive collapse is based on the degree of force redundancy that the structural system of a building has. A Pareto-optimal tradeoff surface formed by a population of conceptual designs for a particular office building project is established in the 3D-space of capital cost, operating cost and income revenue. Computer color filtering of the optimal cost-revenue tradeoff surface is employed to highlight the relative profitability and safety of the different building designs. It is shown that design concepts with the greatest profit potential and those with the greatest safety potential correspond to buildings that also are the least safe and the least profitable, respectively. It is further shown that the capital and operating costs for safer buildings are less than those for more profitable buildings. Computer color filtering of the cost-revenue tradeoff surface is also employed to identify building designs having different window ratios and bay areas, and it is shown that there are multiple compromise building concepts with quite reasonable window ratios and bay areas that are significantly safer than the most profitable buildings while being significantly more profitable than the safest buildings. The paper concludes with some general remarks concerning the design of buildings to withstand or delay progressive collapse under abnormal loading.

Key words: High-rise office buildings, life-cycle profitability, load-path safety, progressive collapse, multi-criteria design, stochastic search, Pareto optimization, computer color-filtering

1 Introduction

A main concern of the owner/builder of a high-rise office building is that there be a profitable relationship between capital cost, operating cost and income revenue over time. Typically, while ensuring proper building performance under normal design loading (gravity, wind, seismic, etc.), designers strive to meet this life-cycle profitability objective by specifying load-carrying structural systems that have large bay areas between columns/shearwalls so as to increase the flexibility of floor space usage. This, and the adoption of large window ratios to take maximum advantage of natural lighting, results in buildings that have good quality office space which commands high annual lease rates.

[1] Kinectrics, Generation Plant Technologies, Toronto, Ontario M8Z 6C4, Canada
email: siavash.khajehpour@kinectrics.com

[2] Civil Engineering Department, University of Waterloo, Ontario N2L 3G1, Canada
email; grierson@uwaterloo.ca (corresponding author)

The tragic failure of the twin towers of the World Trade Center in New York due to terrorist attack on September 11, 2001, will place significant onus on designers of future high-rise marquee buildings to explicitly ensure specified levels of safety against progressive collapse under abnormal loading (impact, blast, fire, etc.). For the particular situation where progressive collapse is triggered by the floor system disengaging from its supports over all or part of the building footprint at a localized story level, as appeared to be the case for the World Trade Center, designers can strive to meet this progressive-collapse safety objective by specifying load-carrying structural systems that have smaller bay areas so as to increase the numbers of girders/columns/shearwalls supporting the floor system. This, and the adoption of floor systems that are well connected to the supporting superstructure, will result in buildings that have high redundancy and thus enhanced load-path safety against progressive collapse.

This paper investigates the tradeoff between life-cycle profitability and load-path safety for an example high-rise office building project. A multi-criteria genetic algorithm is applied to create a number of alternative Pareto-optimal conceptual designs for the building that together form the optimal cost-revenue tradeoff surface in the 3D-space of capital cost, operating cost and income revenue. A life-cycle cost-revenue function and a load-path redundancy function are applied to determine the profit potential and the safety potential, respectively, of the different building designs. Computer color filtering of the cost-revenue tradeoff surface is employed to highlight the differences between building concepts having the greatest life-cycle profit potential over time and those having the greatest load-path safety potential against progressive collapse under abnormal loading. Color filtering of the tradeoff surface is also used to identify compromise designs having intermediate profit and safety potentials. The work extends an earlier study of the same topic (Grierson and Khajehpour 2001), and is based upon a computer-based procedure for conceptual design of engineered artifacts developed by the authors (Khajehpour 2001, Grierson and Khajehpour 2002).

2 Example office building project

Table 1 lists the parameter values governing an example office building design project (Khajehpour, 2001). The land cost is defined by the area of the building footprint. The low-to-high range of annual lease rates is defined by the location of the building and accounts for quality of office space that ranges from poor (small bay areas/low window ratio) to good (large bay areas/high window ratio). The annual cost of maintenance work required to upkeep and clean the building is taken as 2% of the capital cost of the structure, cladding, and HVAC, elevator and lighting systems. The annual cost of property taxes is taken as 5% of the value of the building. Unit costs are U.S. national averages and include account for cost of materials, shipping, unloading, accessories and installation. (Means 1999). The costs of columns, bracing and shear walls for the building are defined by the unit costs for steel, concrete, reinforcement and forming. Floor and staircase costs are defined by US national averages (Means 1999). The finishing unit cost accounts for the cost of painting, carpets and other trim for the building. The unit costs for structural steel and plumbing account for the cost of fire protection. The building mechanical and electrical systems include all-air HVAC systems, electric-traction elevators and fluorescent lighting. The HVAC unit costs account for the cost of boilers, chillers and plumbing required to accommodate the heating and cooling loads imposed on the building. Elevator costs are taken as US national averages, as are those for cladding and windows (Means 1999). The electrical unit cost accounts for the cost of lighting and associated wiring and outlets required to provide an illumination level of 20 Watts/m^2. The energy unit costs account for the cost of the electricity/gas consumed by the HVAC, elevator and lighting systems.

The geographical and environmental information in Table 1 is intended to apply for a city in North America. The load information is specified by the National Building Code of Canada (NRCC 1990). The applied dead load accounts for the weight of wall partitions, ceilings and fixtures, floor finishing and plumbing and ducting. The selfweight of the floors is separately accounted for once the floor type and bay areas are identified. The gravity live load accounts for the weight of office equipment, furnishings and occupants. All gravity dead and live loads are applied as uniformly distributed loads over the entire building footprint area at each story level, including the roof. Lateral wind loads are calculated as a function of the building surface area and the wind pressure listed in Table 1. Both direct and suction wind loading are applied at each story level as equivalent concentrated loads. Seismic loading is not accounted for.

The building architectural systems are specified such that the column lines are regularly spaced in two orthogonal-plan directions. The floor type and depth are taken the same for all stories. Windows are installed one metre above floor level and stretch to the ceiling. The building plan layout, service core area, and floor-to-floor height are specified to be the same for all stories. Table 1 lists the limitations imposed on the building footprint dimensions, overall height, floor-to-ceiling clearance height, centrally located vertical service core area, and corridor (hallway + office) distance from core to building perimeter. The building is to have at least $60{,}000 m^2$ of lease office space after the service core area is accounted for. Table 1 also lists the limitations imposed on the length-to-width aspect ratio and the height-to-width slenderness ratio for the building to comply with good office-space layout principles and required structural stability conditions, respectively.

The dimensional limits listed in Table 1 restrict the building to have from 15 to 80 stories which, for practical design purposes, limits the number of different lateral and gravity load-resisting structural systems that may be considered for the design of the building to the five types shown in Figure 1. Table 2 lists ten possible choices for these structural systems depending on whether they are concrete or steel. Also listed in Table 2 are the different choices possible from among eight floor system types, eight numbers of column bays in either plan direction, sixteen bay widths in either plan direction, four window types, sixteen window ratios, and four exterior cladding types. The eight different floor systems are depicted in Figure 2, where the first four types apply for concrete structures while the last four apply for steel structures.

The ranges of available choices for architectural and structural systems listed in Table 2 allow for a total of more than 167 million design concepts for the building, albeit most are infeasible. A stochastic search technique (Grierson and Khajehpour 2002) is employed in the following to identify a subset of feasible designs that are Pareto-optimal in the sense that for each such design there does not exist any other feasible design for the building that simultaneously has smaller capital and operating costs and larger income revenue.

3 Multi-criteria design optimization

A set of optimal feasible design concepts for the building is found by formulating and solving the multi-criteria optimization problem (Grierson and Khajehpour 2002),

Minimize: *{Initial Capital Cost ; Annual Operating Cost ; 1/Annual Income Revenue}* (1a)

Subject to: *{Dimensional Restrictions ; Availability Limitations ; Performance Requirements}* (1b)

In Eq. (1a), the three cost-revenue objective criteria to minimize initial capital cost, minimize annual operating cost, and minimize 1/annual income revenue (i.e., maximize annual income revenue) for the office building are functions of the governing parameters and primary variables for the design listed in Tables 1 and 2, respectively, as well as of the secondary design quantities that define building width, length and height, number of stories, floor depth, service core dimensions, available lease office space, and aspect and slenderness ratios (the values of which are derived from those for the governing parameters and primary variables).

The initial capital cost at the time of building construction is defined by the cost of land and that of estimated architectural, structural, mechanical and electrical systems found through corresponding approximate analyses. The annual operating cost is defined by the cost of energy consumed, maintenance work done and property taxes for the first year after completion of building construction.

The annual income revenue is that generated for the first year after completion of construction and is defined by the available office space, tenant occupancy rate and annual lease rate The lease rate is established taking into account the location of the building and the quality of office space (Khajehpour 2001). The building location defines minimum and maximum local lease rates (e.g., see Table 1). The quality of office space is a function of the flexibility of floor space usage and the extent of natural lighting, and can be poor or good depending on whether the building has smaller or larger bay areas and window ratio, respectively.

The constraints in Eq.(1b) ensure the feasibility, functionality and performance of the building. The dimensional restrictions are defined by the building limits listed in Table 1. The availability limitations are defined by the ranges of primary design variable values listed in Table 2. The performance requirements ensure that columns, bracing, shear walls and floor systems satisfy design code provisions (CISC 1997, CPCA 1995) under the action of axial, flexural and shear forces calculated using approximate structural analysis for code-specified combinations of dead, live and wind loading (NRCC 1990). Additional constraints are imposed by rules of good design practice that ensure the architectural, structural, mechanical and electrical layouts and systems for the building are feasible and practical (e.g., the first four floor systems listed in Table 2 are only used for concrete frame structures, while the last four floor systems are only used for steel frame structures).

An optimal solution to the problem posed by Eqs.(1) is a design for the building that is not dominated for all three cost-revenue objective criteria by any other possible feasible design. Such a design is termed *Pareto* (Pareto 1896) and, as the following results demonstrate, there are many of them. The Pareto optimization problem is solved using a multi-criteria genetic algorithm (MGA), the flowchart for which is shown in Figure 3. The possible choices for the primary design variables listed in Table 2 are represented by their binary equivalents listed in Table 3. The genetic data and operators adopted for the MGA are: population size = 1000 building design concepts (encoded as binary bit-strings); reproduction = weighted roulette-wheel simulation (proportionate fitness selection); crossover = two-point, with 100% probability; and mutation = single-bit, with probability that decreases from 5% to 0% over successive generations of the genetic search. As indicated in Figure 3, the reproduction, crossover and mutation operators are applied generation-after-generation to the population of designs until, guided by cost-revenue fitness evaluations (with account for constraint violations), the Pareto-optimal design set for the building is found (to remain the same for a specified number of consecutive generations), at which point convergence is taken to occur and the genetic search terminates.

4 Building design results

The computer-based MGA finds 815 Pareto designs that together define the optimal cost-revenue tradeoff surface depicted in Figure 4 in the 3D-space of capital cost, operating cost and 1/income revenue for the building (Khajehpour 2001). Each of the 815 (grayscale) dots plotted in Figure 4 corresponds to a different design of the building. For example, the building design corresponding to the single dot circled in Figure 4 is shown in Figure 5. This building has a steel moment-frame and concrete shearwall structural system (Figure 1), and a steel joist, beam and deck floor system topped by a concrete slab (Figure 2). It is 122m high and has thirty-one floors (including one mechanical floor). The plan footprint area at each floor level is 50m x 50m = 2500m^2 divided into fifty 5m x 10m = 50m^2 bay areas. A central service core area of 15.6m x 32.1m = 500m^2 at each floor level accommodates twenty-one elevators and two staircases over the height of the building. Insulated heat absorbing windows occupy 60% of the available window surface on the building perimeter. The remaining perimeter surface of the building is clad with metal siding panels. The total amount of available lease office space is 60,000m^2. The annual lease rate for office space is \$371.4/m^2 (US\$), as determined by the bay area size and window ratio (Khajehpour 2001). The initial capital cost and annual operating cost for the building are \$102.48M(million) and \$8.68M, respectively. Assuming all office space is leased, the annual income revenue for the building is \$22.28M.

Only eight of the ten structural systems listed in Table 2 were found to be represented in the Pareto-optimal design set, as buildings with a concrete or steel framed tube structural system did not survive as viable cost-revenue design concepts (Khajehpour 2001). All eight of the floor systems listed in Table 2 are represented in the Pareto-optimal design set. From among all 815 Pareto-optimal designs: the shortest building is 19 stories high and has a plan footprint that measures 70m x 60m, while the tallest building has 52 stories and a 50m x 30m plan footprint; the minimum and maximum total lease office spaces are 60,000m^2 and 61,740m^2, respectively, a difference of less than 3%; the minimum and maximum bay area sizes are 25m^2 and 132m^2, respectively; the minimum and maximum window ratios are 25% and 100%, respectively; and the minimum and maximum annual lease rates are \$305/m^2 and \$497/m^2, respectively.

Computer color filtering of the cost-revenue tradeoff surface formed by the Pareto-optimal design set (Figure 4) is carried out in the following to identify zones occupied by building concepts having either the greatest life-cycle profit potential over time or the greatest load-path safety potential against progressive collapse.

5 Life-cycle profitability

Having the values of initial *Capital Cost*, annual *Operating Cost* and annual *Income Revenue* for each of the Pareto-optimal design solutions to the problem posed by Eqs.(1), the life-cycle profit potential over time of each of the corresponding buildings is assessed by evaluating the cost-revenue function,

$$
\begin{aligned}
Profit = \; & Income\ Revenue * \sum_{k=1}^{t} [\, OR_k * (1+MR)^{t-k} * (1+IR)^{k-1} \,] \\
& - Operating\ Cost * \sum_{k=1}^{t} [\, (1+MR)^{t-k} * (1+IR)^{k-1} \,] \\
& - Capital\ Cost * (1+MR)^{t}
\end{aligned}
\qquad (2)
$$

where OR_k is a variable annual tenant occupancy rate, *MR* and *IR* are fixed annual mortgage and inflation rates, respectively, k = a yearly counter, and t = the time in years after completion of construction.. A time interval-halving technique is applied to Eq.(2) to find the time $t = t^o$ for each Pareto design when *Profit* changes from a negative to a positive value. The relative life-cycle profitability of each building is characterized by a profitability index calculated as,

$$Profitability\ Index = t^{min} / t^o \tag{3}$$

where t^{min} is the minimum period of time after completion of construction when a building in the Pareto set begins to become profitable (i.e., when *Profit = 0)*. From Eq.(3), the building for which $t^o = t^{min}$ has the greatest *Profitability Index = 1*, while buildings for which $t^o > t^{min}$ have smaller *Profitability Index < 1*.

The computer color-filtered graphic of the optimal cost-revenue tradeoff surface shown in Figure 6 highlights zones of different life-cycle profitability among the 815 Pareto designs for the building (these results were determined through Eqs. (2) and (3) for the mortgage and inflation rates given in Table 1, for annual income revenue calculated for a tenant occupancy rate that is 55% for the first year and which increases 10% yearly until reaching a maximum level of 95% for the fifth year and thereafter, for annual operating cost calculated assuming the building is fully operational each year, and assuming that the entire initial capital cost of the building is mortgaged). The building with the greatest profit potential corresponds to the black dot circled in Figure 6 (*Zone 1*), and is shown in Figure 7. This building is the first to become profitable, 10.1 years after completion of construction, primarily because it commands a high annual lease rate of $497/m^2 due to the fact that it has the highest possible window ratio of 100% and reasonably large bay areas of 8.5m x 12m = 102m^2, which give rise to good quality office space having lots of natural daylight and fairly flexible floor usage possibilities.

6 Load-path safety

Having the numbers of bay areas and columns that define the plan footprint of each Pareto-optimal building design, the load-path safety potential against progressive collapse triggered by the failure of the entire floor system at a localized story level is assessed by evaluating the force redundancy function,

$$R = \{\ C * (\ Number\ of\ Bay\ Areas + Number\ of\ Columns - 1)\ \} \tag{4}$$

where R = the degree of force redundancy (indeterminacy) at any one story level of the building, and C = the degree of force connectivity between the floor system and the girders/columns/shearwalls (e.g., $C = 6$ indicates full bi-axial moment, bi-axial shear, axial and torsional force connectivity of the floor system in all bay areas). The greater the value of R from Eq.(4) the greater is the load-path redundancy of the building and, hence, the greater is its load-path safety against progressive collapse under abnormal loading. The relative load-path safety of each building is characterized by a safety index calculated as,

$$Safety\ Index = R / R^{max} \tag{5}$$

where R^{max} is the maximum load-path redundancy among all buildings in the Pareto-optimal design set. From Eq.(5), the building for which $R = R^{max}$ has the greatest *Safety Index = 1*, while buildings for which $R < R^{max}$ have smaller *Safety Index < 1*.

The computer color-filtered graphic of the optimal cost-revenue tradeoff surface shown in Figure 8 highlights zones of different load-path safety among the 815 Pareto designs for the building (these results were determined through Eqs. (4) and (5) assuming that the degree of connectivity between the floor system and its supporting girders/columns/shearwalls is the same for all buildings). Figure 8 indicates that three buildings have the same maximum safety potential (*Zone 4*), the circled one of which is shown in Figure 9. These buildings have the largest load-path redundancy from among all Pareto designs because they have the smallest bay areas (5m x 5m = 25m^2) and, consequently, proportionally larger numbers of girders/columns/shearwalls available to carry loads.

7 Profitability versus safety

It is interesting to note from Figures 7 and 9 that the building with the greatest safety potential has both lower initial capital cost ($100.62M versus $107.98M) and lower annual operating cost ($8.60M versus $8.91M) than the building with the greatest profit potential. This is because the floor and façade capital costs and the HVAC operating costs are greater for the latter building by virtue of its larger bay areas and window ratio. Indeed, upon comparing Figures 6 and 8 it can be observed that safer buildings are viable cost-revenue design concepts because they have lower capital and/or operating costs than other designs, while more profitable buildings are viable design concepts because they generate more income revenue than other designs.

Compared to the building with the greatest profit potential shown in Figure 7, the building with the greatest safety potential shown in Figure 9 commands a somewhat lower annual lease rate of $305/m^2 because it has poorer quality office space as a consequence of having a low window ratio of 25% and the small 25m^2 bay areas noted above. As a result, Figures 7 and 9 reveal that the time-to-profitability for the safest building is more than three times that for the most profitable building. At the same time, however, Figures 7 and 9 also reveal that the load-path redundancy of the most profitable building is less than one-third of that for the safest building and, therefore, that it has somewhat less safety potential against progressive collapse under abnormal loading.

Indeed, the two buildings in Figures 7 and 9 represent extremes of the set of designs forming the optimal cost-revenue trade-off surface (Figure 4), in the sense that the most profitable building has almost the least safety potential against progressive collapse while the safest building has almost the least profit potential over time. Perhaps a design that represents a compromise between the two would be a better choice for the building project. One such compromise building design is that shown in Figure 5 which, as indicated by its profitability and safety indices, has twice the safety potential (load-path redundancy) of the most profitable building and twice the profit potential (half the time-to-profitability) of the safest building. This building has a 60% window ratio and 50m^2 bay areas.

In fact, there are multiple alternative building concepts with quite reasonable window ratios and bay areas that are significantly safer than the most profitable building while being significantly more profitable than the safest building. To illustrate this, the optimal cost-revenue tradeoff surface has been computer color filtered in Figures 10 and 11 to identify zones occupied by building concepts having different window ratios and bay areas, respectively. The intersection of *Zones 3, 2, 2,* and *3* in Figures 6, 8, 10 and 11, respectively, identifies the cluster of building design concepts circumscribed by a box in Figure 4 that have 45-65% window ratios and 77-105m^2 bay areas, and which are twice as safe and profitable as the most profitable and safest buildings, respectively. These alternative building designs have steel moment frames with bracing and, at 19 to 27 stories high, are shorter with larger footprint plan areas than both the most profitable and safest buildings (Khajehpour 2001). They require larger building site areas to accommodate their larger footprints and as a consequence, because the cost of land is expensive at \$12,000/m^2 (Table 1), they have greater initial capital cost than both the most profitable and safest buildings. At the same time, these alternative buildings incur lower annual operating cost than the most profitable building and generate higher annual income revenue than the safest building.

From Figure 7, the most profitable building is a concrete frame/shearwall structure with concrete floors while, from Figure 9, the safest building is a steel frame/concrete shearwall structure with steel/concrete floors. It is important to note, however, that the tradeoff between profitability and safety is not dependent on whether buildings are primarily concrete or steel. In fact, several of the high profit-potential buildings in *Zone 2* of Figure 6 are steel frame/concrete shearwall structures with steel/concrete floors, while two the three buildings indicated in *Zone 4* of Figure 8 as having the maximum safety potential are concrete frame/shearwall structures with concrete floors (Khajehpour 2001).

8 Concluding Remarks

The relative safety (load-path redundancy) results highlighted in Figure 8 were found assuming that all of the floor system types listed in Table 2 have the same degree of connectivity with their supporting girders/columns/shearwalls for the building. In reality, however, some types of floor systems provide lower load-path redundancy than do other floor systems. For example, only the top chords of an open-web steel joist floor system of the type used in the World trade Center are end-connected by bolts or welds to horizontal bearing-support girders that span between column lines. Even though both the top and bottom chords are typically end-connected at the column lines themselves, the load-path safety (redundancy) of such a floor system is somewhat less than that of, say, a concrete plate or slab floor system that is monolithically connected to the girders/columns/shearwalls for the building. Indeed, if the steel joist floor system is subjected to intense fire loading it will begin to sag in span and the bolts or welds at the ends of the top chords will become particularly vulnerable to failure in shear as the otherwise bearing connections become loaded into tension (Kirby 1999), thereby potentially triggering progressive collapse of the building. As another example, panelized concrete buildings are vulnerable to progressive collapse failure under blast loading if the floors and bearing walls are not adequately connected (Griffiths *et al.* 1968). The importance of load-path redundancy for the safety of buildings of any type should never be underestimated, as evidenced by the 1990's bombing of the Murrah Federal Building in Oklahoma City which initially destroyed only a single column but that was sufficient to trigger a progressive collapse failure that claimed a majority of the casualties (Rittenhouse 1995, Brouwer 2002)

The problem of progressive collapse under abnormal loading is very complex and challenging (Burnett 1974), and the work presented here concerning load-path redundancy addresses but a part of the solution. It is also necessary to ensure that the lateral and gravity load-resisting structural systems for a building have adequate strength and ductility to prevent or impede progressive collapse under prescribed abnormal loading. For example, even though the open-web steel joist floor system discussed in the previous paragraph is quite cost-effective for long spans, under intense fire loading it may be required to end-connect all top and bottom chord members to prevent or impede progressive collapse triggered by the floor breaking away from the columns/girders/shearwalls for the building. Similarly, even though the monolithic concrete flat plate floor system for the concrete structure in Figures 7 is also quite cost-effective because it serves to limit the overall building height, under intense blast loading it may need to be reinforced by drop panels and column capitals to prevent or impede punching shear failure leading to progressive collapse (Ettouney *et al*. 1996). Fire loading is also of significant concern for concrete structures because under intense heat concrete is prone to explosive thermal spalling, thermal fracture, and disintegration due to dehydration (Bazant and Kaplan 1996), which may require the building superstructure to be augmented in a variety of ways so as to prevent or impede local failure leading to progressive collapse.

The foregoing discussion is not suggesting that it is always possible to build tall buildings that would never fail under the action of abnormal loading such as that experienced by the World Trade Center. It is implying, however, that a variety of design strategies can be employed to construct buildings that are able to stand up under abnormal loading as long as long as possible so as to give tenants and rescue personnel a reasonable chance to evacuate before the devastating cascading effects of progressive collapse occur. The results presented concerning building life-cycle profitability were originally reported in February 2001 (Khajehpour 2001), while those concerning building load-path safety were found in the months following September 11, 2001. The calculation of income revenue in both cases was based on the premise that larger and more open office space with lots of windows commands a higher annual lease rate.. It may be that tenants in the future will, instead, prefer to pay higher annual lease rates for office space in marquee buildings that are specifically designed to have greater safety against progressive collapse under abnormal loading.

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List of Tables and Figures

Table 1: Governing parameters for office building design

Parameter	Value
Location Information	
Land Unit Cost (US\$/m^2)	12000
Range of Annual Lease Rates (\$/m^2/yr)	300-540
Maintenance (%capital cost)	2
Taxes (%building value)	5
Mortgage Rate (%)	10
Inflation Rate (%)	3
Unit Costs	
Structural steel (\$/ton)	2039
Concrete (\$/m^3)	143
Reinforcement (\$/ton)	1400
Forming (\$/m^2)	45
Roofing (\$/m^2)	63
Finishing (\$/m^2)	130
Plumbing (\$/m^2)	45
HVAC Boiler (\$/kW)	225
HVAC Chillers (\$/kW)	715
Energy-Electric (\$/mWhr)	100
Energy-Gas (\$/mWhr)	40
Electrical (\$/m^2)	121
Elevators, cladding, windows (\$/avgUS\$)	1
Geographical & Orientation Information	
Latitude (Degree North)	40
Angle of building with East (Degree)	0
Environmental Information	
Clear Sky Percentage (%)	75
Hot Day Relative Humidity (%)	80
Cold Day Relative Humidity (%)	50
Inside Temperature (C^0)	22
Average Maximum Outside Temperature (C^0)	31
Average Minimum Outside Temperature (C^0)	– 20
Hot Day Temperature Range (C^0)	10
Cold Day Temperature Range (C^0)	10
Load Information	
Applied Dead Load (kN/m^2)	1.45
Gravity Live Load (kN/m^2)	2.80
Wind Load Pressure (kPa)	0.48
Seismic Load	N/A
Building Limits	
Maximum Footprint Length (m)	70
Maximum Footprint Width (m)	70
Maximum Building Height (m)	300
Minimum Floor/Ceiling Clearance (m)	3
Fixed Core/Footprint Area (%)	20
Minimum Core/Perimeter Distance (m)	7
Minimum Lease Office Space (m^2)	60,000
Maximum Length-to-Width Aspect Ratio	2
Maximum Height-to-Width Slenderness Ratio	9

Table 2: Primary variables for office building design

Index	Structural System Type	Floor System Type	BayNumber (x , y)	BayWidth (m)	Window Type	WRatio (%)	Cladding Type
1	Concrete *m*-frame	Concrete flat plate	3	4.5	Standard	25	*PC* concrete
2	Concrete *m*-frame & shearwall	Concrete flat slab	4	5.0	Insulated	30	Metal panel
3	Concrete framed tube	Concrete waffle slab	5	5.5	Standard *HA*	35	Stucco wall
4	Steel *m*-frame	Concrete beam & slab	6	6.0	Insulated *HA*	40	Glazed panel
5	Steel *g*-frame & bracing	Composite steel beam & concrete slab	7	6.5		45	
6	Steel *m*-frame & bracing	Steel joist & beam & deck & concrete slab	8	7.0		50	
7	Steel *g*-frame & concrete shearwall	Steel beam & composite deck & concrete slab	9	7.5		55	
8	Steel *m*-frame & concrete shearwall	Composite steel beam & deck & concrete slab	10	8.0		60	
9	Steel *g*-frame & bracing & outriggers			8.5		65	
10	Steel framed tube			9.0		70	
11				9.5		75	
12				10.0		80	
13				10.5		85	
14				11.0		90	
15				11.5		95	
16				12.0		100	

BayNumber = number of column bays in the x and y directions of the building footprint (8 choices in either direction) ; BayWidth = width of column bays in the x and y directions (16 choices in either direction) ; WRatio = window ratio ; g = gravity ; m = moment ; HA = heat absorbing ; PC = Pre-Cast

Table 3: Binary representation of primary variables for office building design

Base-10 Index	Structural System Type	Floor System Type	BayNumber (x , y)	BayWidth (m)	Window Type	WRatio (%)	Cladding Type
1	0000	0000	0000	0000	0000	0000	0000
2	0001	0001	0001	0001	0001	0001	0001
3	0010	0010	0010	0010	0010	0010	0010
4	0011	0011	0011	0011	0011	0011	0011
5	0100	0100	0100	0100		0100	
6	0101	0101	0101	0101		0101	
7	0110	0110	0110	0110		0110	
8	0111	0111	0111	0111		0111	
9	1000			1000		1000	
10	1001			1001		1001	
11				1010		1010	
12				1011		1011	
13				1100		1100	
14				1101		1101	
15				1110		1110	
16				1111		1111	

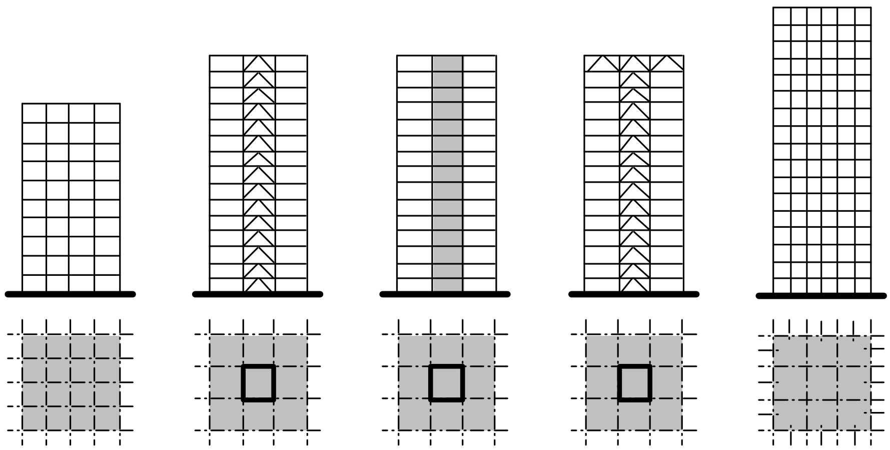
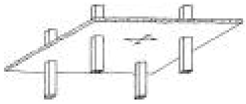
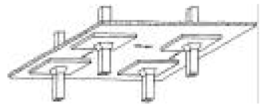


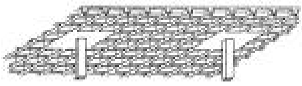
Figure 1: Structural system types



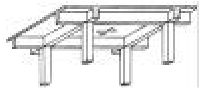
a) Concrete flat plate



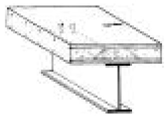
b) Concrete flat slab



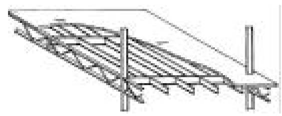
c) Concrete waffle slab



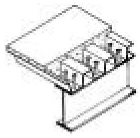
d) Concrete beam & slab



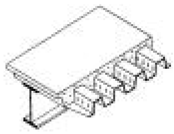
e) Composite steel beam & concrete slab



f) Steel joist & beam & deck & concrete slab



g) Steel beam & composite deck & concrete slab



h) Composite steel beam & deck & concrete slab

Figure 2: Floor system types

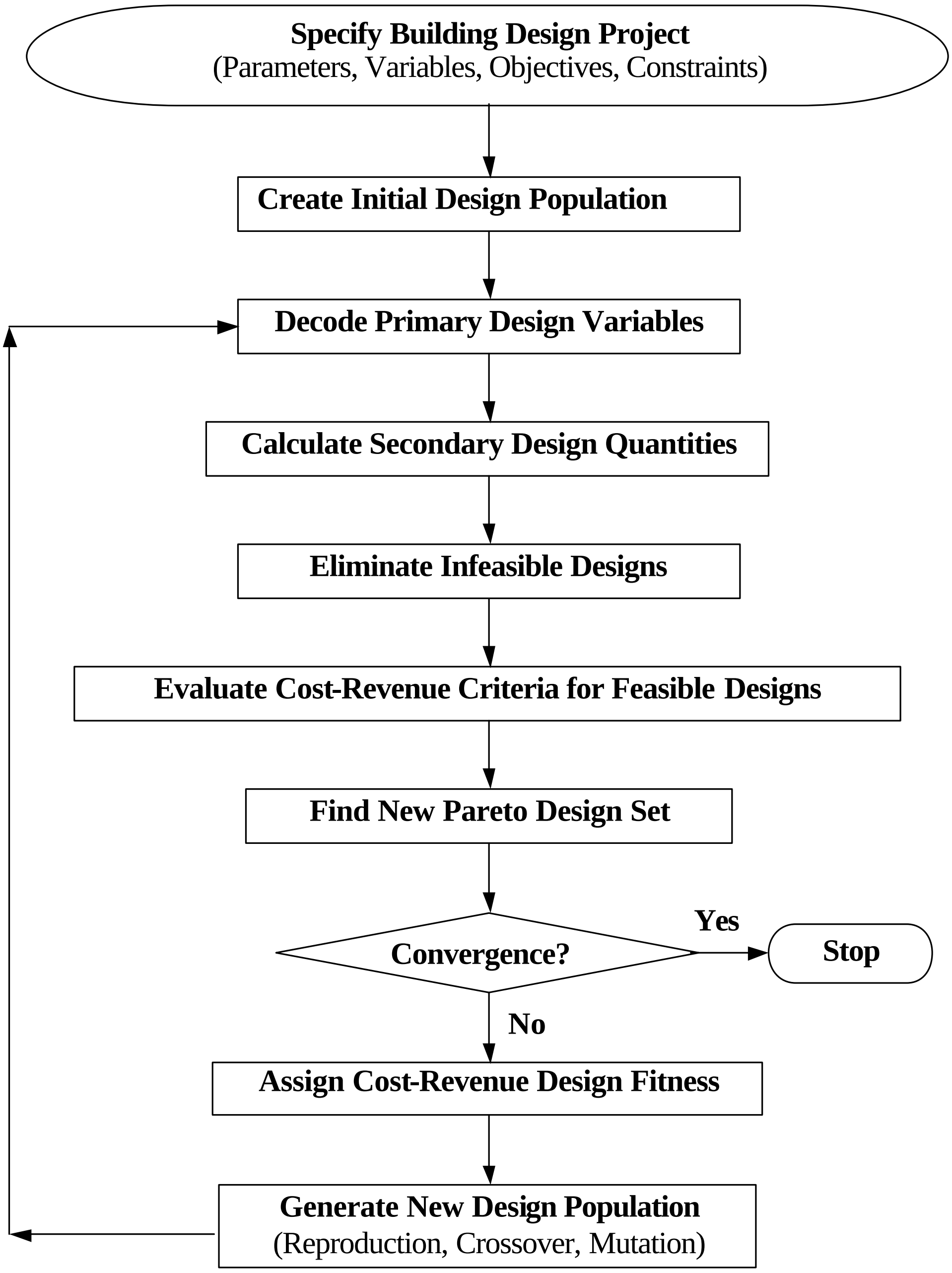


Figure 3: Multi-criteria Genetic Algorithm (MGA)

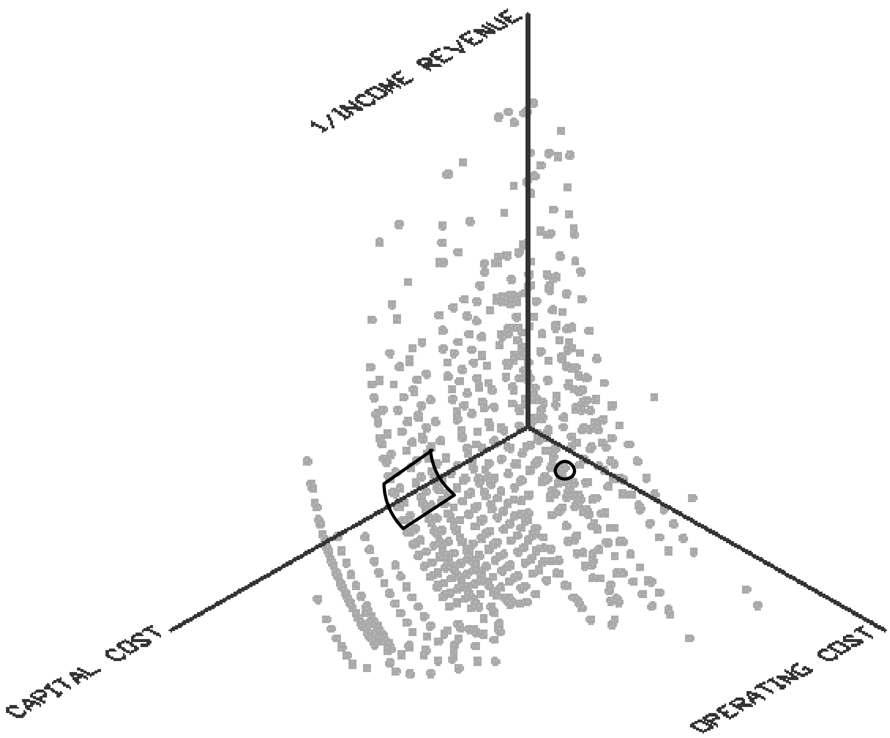


Figure 4: Optimal cost-revenue trade-off surface

Structure: Steel moment frame & concrete shearwall
Floor: Steel joist & beam & deck & concrete slab
Number of floors: 31
Height: 122m
Footprint: 50m x 50m
Bay area: 10 m x 5m
Core area: 32.1m x 15.6m
Elevators: 21
Staircases & width: 2 @ 1.1m
Window : Insulated heat absorbing
Window ratio: 60%
Cladding: Metal siding panel
Lease office space: 60000m^2
Annual lease rate: \$371.4 /m^2
Initial capital cost: \$102.48M
Annual operating cost: \$8.68M
Annual revenue income: \$22.28M
Profitability index: 0.58 (n = 17.5 yrs)
Safety index: 0.52 (R = 115* C)

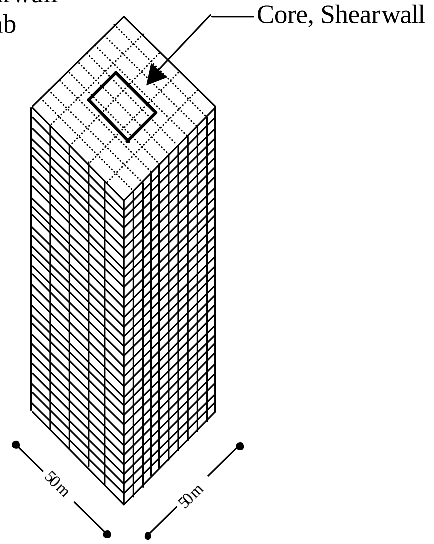


Figure 5: Example Pareto-optimal building design

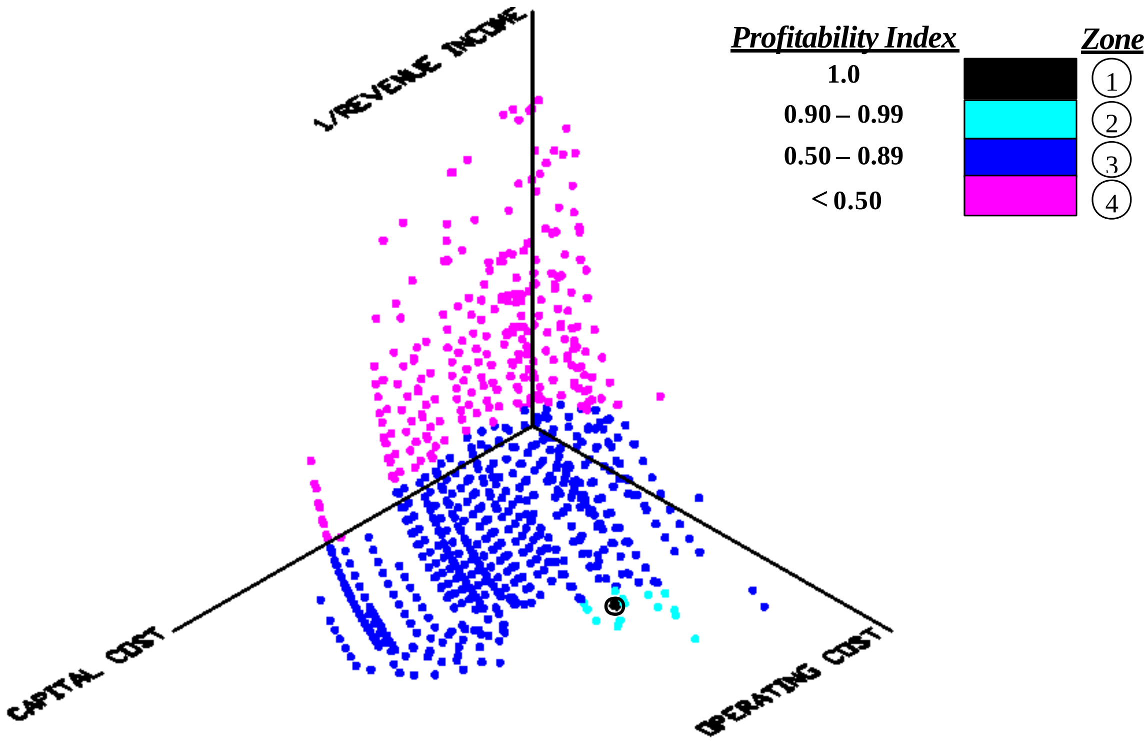


Figure 6: Building life-cycle profitability

Structure: Concrete moment frame & shearwall
Floor: Two-way concrete flat plate
Number of floors: 32
Height: 122m
Footprint: 68m x 36m
Bay area: 8.5m x 12m
Core area: 38.4m x 12.8m
Elevators: 21
Staircases & width: 2 @ 1.1m
Window : Insulated heat absorbing
Window ratio: 100%
Cladding: Metal siding panel
Lease office space: 60651m^2
Annual lease rate: \$497/m^2
Initial capital cost: \$107.98M
Annual operating cost: \$8.91M
Annual revenue income: \$30.14M
Profitability Index: 1.0 (n = 10.1 yrs)
Safety Index: 0.27 (R = 59* C)

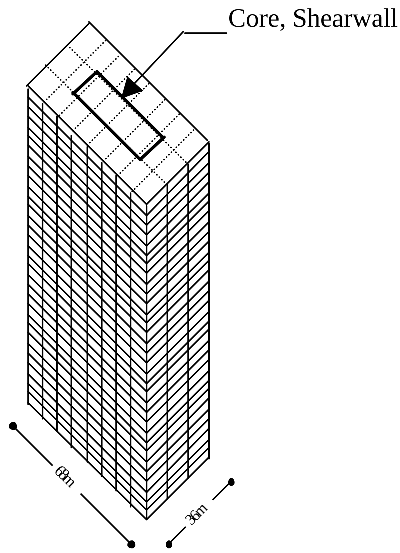


Figure 7: Most profitable building

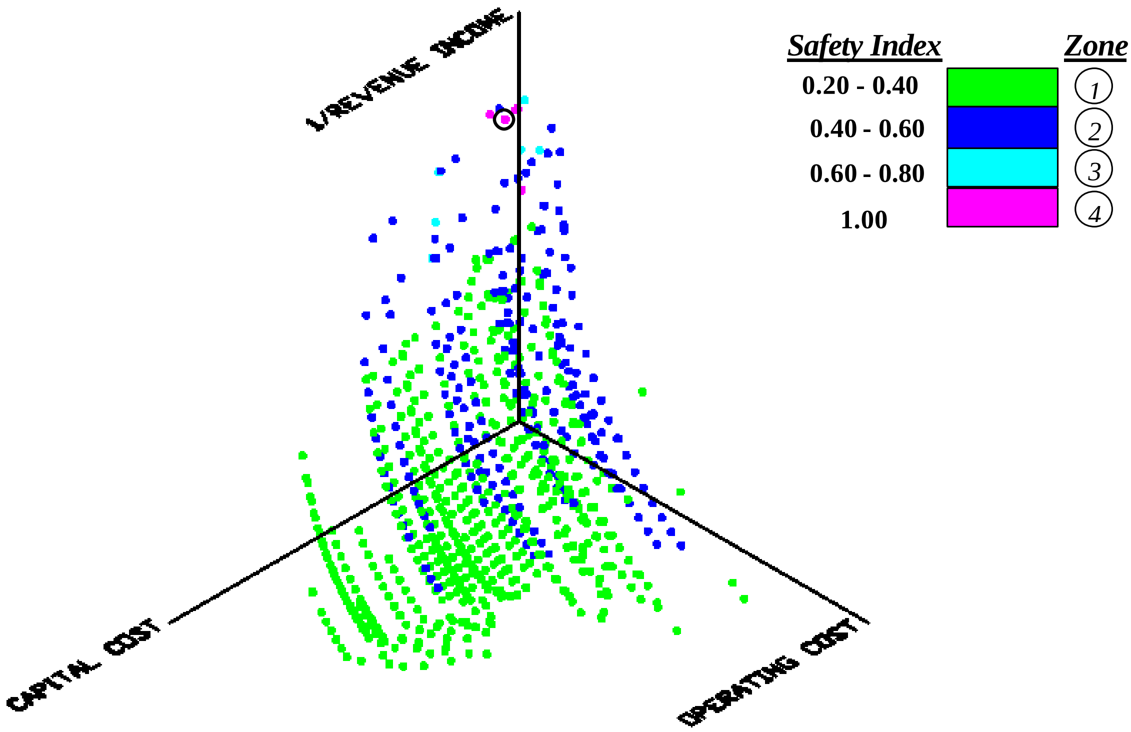


Figure 8: Building load-path safety

Structure: Steel moment frame & concrete shearwall
Floor: Steel joist & beam & deck & concrete slab
Number of floors: 31
Height: 116m
Footprint: 50m x 50m
Bay area: 5m x 5m
Core area: 20.6m x 24.3m
Elevators: 21
Staircases & width: 2 @ 1.1m
Window : Insulated heat absorbing
Window ratio: 25%
Cladding: Metal siding panel
Lease office space: 60000m^2
Annual lease rate: \$305/m^2
Initial capital cost: \$100.62M
Annual operating cost: \$8.6M
Annual revenue income: \$18.3M
Profitability Index: 0.29 (n = 34.6 yrs)
***Safety Index*:** 1.0 (R = 220* C)

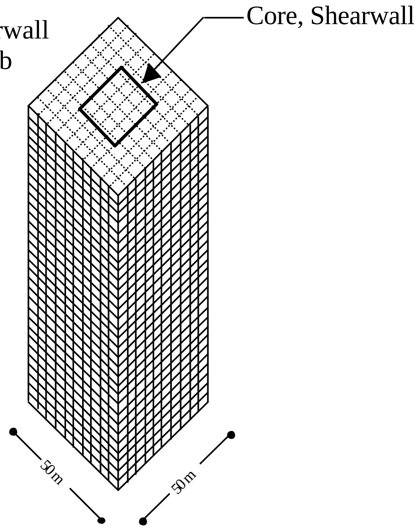


Figure 9: Safest building

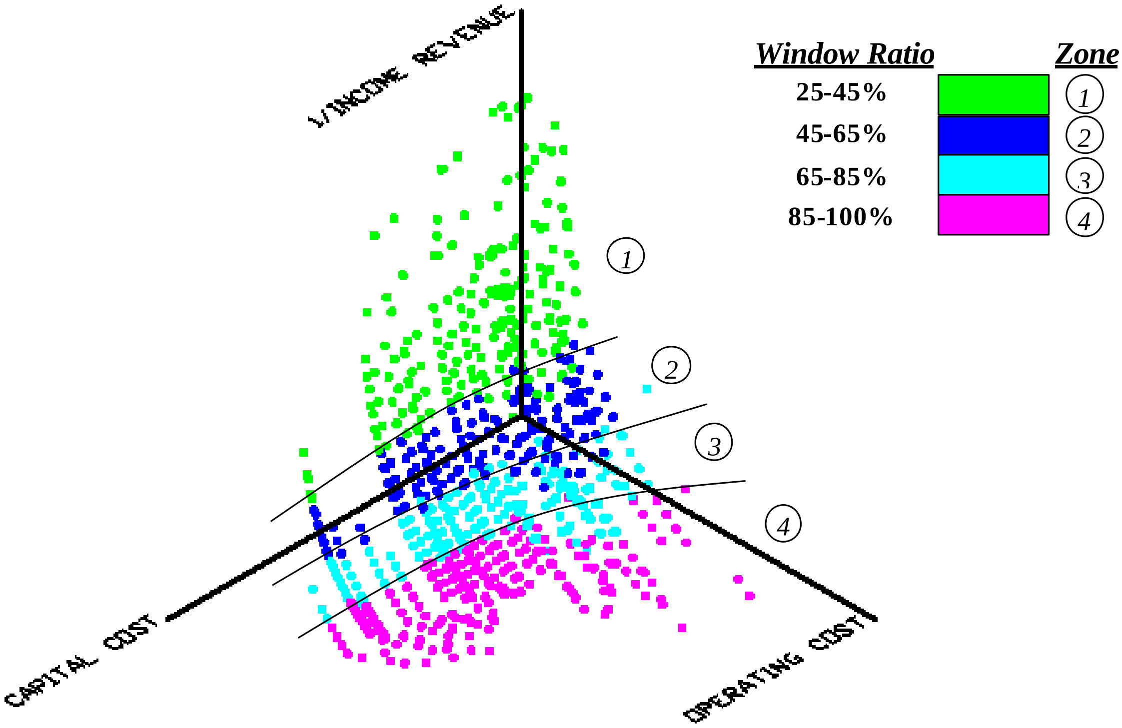


Figure 10: Building window ratios

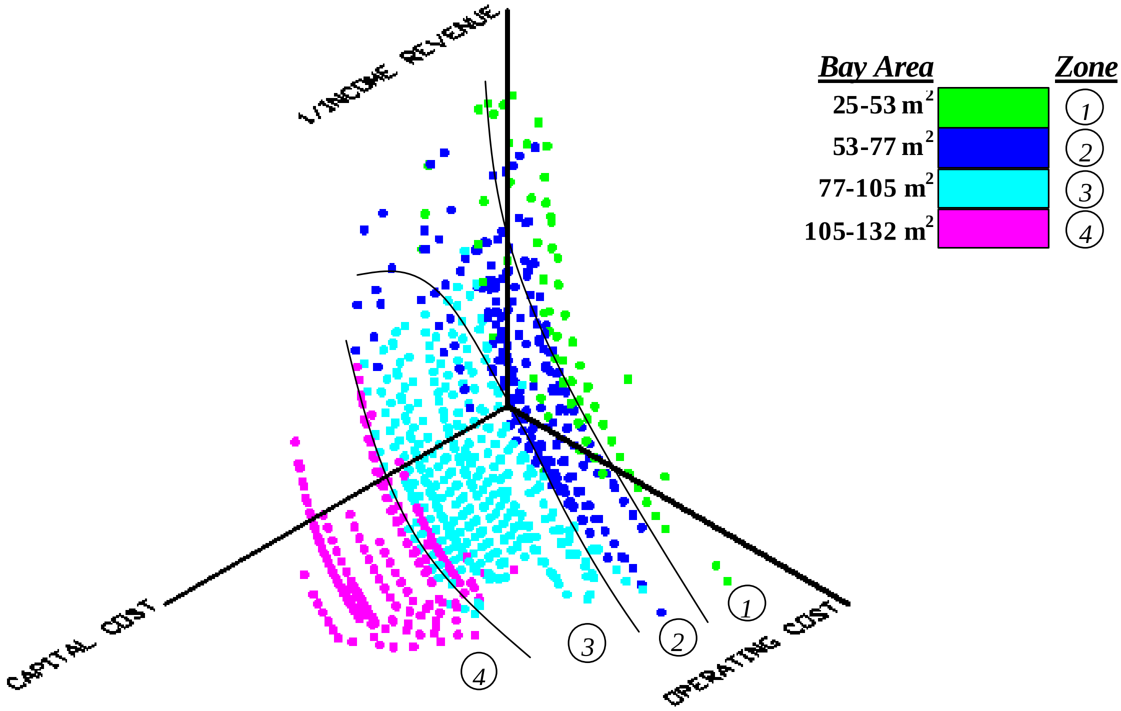


Figure 11: Building bay areas