Chapter 3

Computer-Based Conceptual Design for High-Rise Buildings

3.1 INTRODUCTION

It is proposed in this study that the optimal conceptual design of the major systems for a high-rise building is effectively done through the following three objective criteria: 1) ***minimize initial capital cost***, which consists of the cost of land, structure, façade (cladding and windows), HVAC and elevator systems, lighting, and finishing (painting, carpets, etc); 2) ***minimize annual operating cost***, which consists of maintenance and upkeep costs, the cost of energy consumed per year by the HVAC, elevator and lighting systems, and annual property taxes; and 3) ***maximize annual revenue income***, which is quantified by accounting for the impact that flexibility of floor space usage and occupant comfort level has on lease/rental income. The conceptual design process to achieve these objectives is controlled by multiple constraints concerned with the feasibility, functionality and performance of the building. For this study, explicit constraints are imposed on the building footprint dimensions and height to satisfy available land restrictions and zoning regulations, on the available lease office space to meet anticipated occupancy demands, on the service core area to meet lateral bracing and vertical service requirements, on the distance between the building perimeter and the service core to meet horizontal occupancy requirements, and on the building aspect ratio and slenderness ratio to ensure that designs are compliant with accepted office space layout principles and structural stability requirements. Further implicit constraints are imposed by the limits that are placed on the values of the design variables for an office building, such as the restrictions placed on the type and number of different structural systems, floor systems, cladding types, window types, window ratios and floor plan layouts that may be considered for the design of the building. Additional implicit constraints are imposed by rules of good design practice that ensure architectural, structural, mechanical and electrical systems are feasible and practical.

Recalling the multitude of structural, mechanical and electrical systems discussed in Chapter 2, one can see that optimizing a high-rise office building is extremely complex, and that sometimes the input may seem unmanageable. In fact, generating the best possible design concepts for a building while considering a variety of competing criteria requires the use of numerical algorithms capable of multi-criteria optimization. In this regard, the relatively recent development of search and prediction engines such as Genetic Algorithms (GA's) has created a unique opportunity to solve complex multi-criteria optimization problems. Studies to date have shown that such adaptive search techniques with emergent solution characteristics provide a computing paradigm that is well suited to the complicated and unstructured nature of the conceptual design process (Grierson 1997). The basic features of GA's are briefly elaborated upon in Appendix 3.C. This study proposes to employ a Multicriteria Genetic Algorithm (MGA) for solution of the multi-objective optimization problem posed by the conceptual design of a high-rise office building.

3.2 MULTI-CRITERIA OPTIMIZATION

As building design problems generally have several to many conflicting and non-commensurable criteria, the designer must look for good compromise designs by trading off performance between the various requirements. Multi-criteria optimization offers a flexible approach for the designer to treat this decision-making process in a systematic way.

The two general approaches to solving multi-criteria optimization problems are ‘preference’ and ‘non-preference’ methods. The preference method makes use of explicit information about the relative importance of the different objective criteria in order to identify a best overall solution. A difficulty with this approach is that it is not always possible to assess the relative weightings of the different objective criteria so as to achieve a single (combined) criterion objective. The non-preference method makes no assumptions about the relative importance of the different objective criteria, but, instead, identifies a field of solutions that are all considered to be of equal rank in the sense that no one solution is better than any other solution in the field for all objective criteria. A difficulty with this approach is that the number of these non-dominated solutions is often quite large.

In the absence of specific information about preferred relative weighting of costs and revenues for office buildings, non-preferential optimization is adopted in this study for solution of the multi-criteria conceptual design problem to minimize capital cost, minimize operating cost and maximum income revenue. The basic principles of the non-preferential approach, referred to in the literature as ‘Pareto’ optimization, are described in Appendix 3.D.

The multi-criteria optimization problem posed by this study for the conceptual design of a high-rise office building is concisely stated as,

Minimize:	*{Capital Cost, Operating Cost, 1/ (Revenue Income)}*	(3.1a)
Subject to:	*Explicit Constraints ; Implicit Constraints*	(3.1b)

Note that minimizing the inverse function *1/(Revenue Income)* is equivalent to maximizing revenue income, as desired. The explicit functional forms of the objective and constraint functions in Eqs. (3.1) are first developed in the following sections. Then described is the multi-criteria genetic algorithm (MGA) and overall computational procedure employed by this study to solve the problem posed by Eqs. (3.1)

3.2.1 Capital Cost

The assessment of design alternatives at the conceptual stage of design involves comparison of estimated costs. In general, cost estimates can be produced in increasing level of detail and accuracy by the following approaches:

1. Use unit area cost indices published by reputable organisations (e.g., Means manuals (1999)).
2. Use unit volume cost indices for assemblies, also published by reputable organizations (e.g., Means manuals (1999)).
3. Interface the computer-based design system to a cost-analysis software package (such as *Precision Estimating* (1999) by Timberline Software Corporation) to

perform detailed cost estimates of the design alternatives based on material and labour estimates.

4. Also perform life-cycle cost analysis of design alternatives so that, in addition to construction costs, cost factors such as taxes, mortgage and inflation rates, maintenance and energy costs, in addition to revenue income, are also taken into account.

The first and second cost estimation methods noted above are initially employed, based on cost data extracted from Means Manuals (R.S. Means, 1999), as the means to identify the Pareto optimality of different design alternatives. The fourth cost estimation method noted above is subsequently used to account for life-cycle costing so as to estimate the potential profitability of Pareto-optimal designs over time. The effect that different construction materials have on the duration of construction is neglected when estimating costs since it can be argued that the overall project times for both steel and concrete building construction are very similar (Glover 1991). Furthermore, it is assumed that no interest is accumulated on borrowed money during the construction period, i.e., that life-cycle costing only commences upon completion of the project.

The calculation of initial capital cost at the time of building construction accounts for the cost of land and that of estimated structural (floors, columns, lateral load resisting system, and stair cases), mechanical and electrical (HVAC, elevators, lighting and power outlets) systems found through corresponding approximate analyses, in addition to the cost of the building exterior envelope (facade and roofing) and interior environment (finishing and partitioning), i.e.,

$$\textit{Capital Cost} = \textit{Cost}\{\textit{Land, Floors, Columns, Lateral load system, Stairs, Façade, Roof,}\\ \textit{Finishing, Partitions, HVAC, Elevators, Lighting}\} \quad (3.2)$$

In Appendix 3.A, the capital costs of the individual components in Eq. (3.2) are expressed as explicit functions of the parameters and variables defined in Section 2.3 of Chapter 2 (the reader is also encouraged to refer to the Notation list at the beginning of this study as the written definitions of these parameters and variables are not repeated in Appendix 3.A for the sake of brevity). The total capital cost of a particular conceptual design of an office building is taken by this study to be the sum of the capital costs of the individual building components described in Sections 3.A.1 to 3.A.10 of Appendix 3.A, plus 6% for engineering fees and 25% for contract fees broken down as 10% general requirements + 5% overhead + 10% profit (Mean's Manuals 1999), plus the cost of land.

3.2.2 Annual Operating Cost

The calculation of annual operating cost (after completion of building construction) accounts for the annual cost of energy consumed, maintenance work done and property taxes, i.e.,

$$\textit{Operating Cost} = \textit{Cost}\{\ \textit{Energy, Maintenance, Taxes}\ \} \tag{3.3}$$

Where: the cost of energy is a function of the energy consumed by the HVAC, elevator and lighting systems, as well as by electrical office equipment (which, in turn, is a function of the lease office space); the cost of building maintenance work is a function of the upkeep costs for the HVAC, elevator and lighting systems, and the cleaning and upkeep costs for the building; and the cost of property taxes is a function of the tax rate (as defined by local location information) and the building value.

Refer to Appendix 3.B for a description of the operating costs of the individual components in Eq. (3.3). The total annual operating cost for any particular conceptual design of an office building is calculated by this study as the sum of the annual costs identified in Sections 3.B.1 to 3.B.3 of Appendix 3.B.

3.2.3 Annual Revenue Income

The calculation of annual income revenue after completion of building construction is premised on the concept that higher quality of office space commands higher lease rates, and that income revenue can be quantified in terms of quality of office space and building lease rates, i.e.,

$$\textit{Income Revenue} = \textit{Revenue}\{\textit{Space Quality, Lease Rate}\} \qquad (3.4)$$

The functional forms for space quality and lease rates employed by this study are developed in the following.

3.2.3.1 Quality of Space

The space quality term in Eq (3.4) is taken to be a function of the flexibility of floor space usage, as defined by the extent of column free area, and the comfort level of the occupants, as defined by the ratio of floor area benefiting from natural lighting to the total rentable floor area. The column free area is defined by the CFA factor found through Eq. (2.9e) developed in Section 2.3.3 of Chapter 2. Occupant comfort is defined by the area shown in grey in Figure 3.1 that benefits from natural lighting for a window ratio WIR =

100%; the depth of natural light penetration is considered to be twice the clear height h_{cle} of the story (Reid 1990).

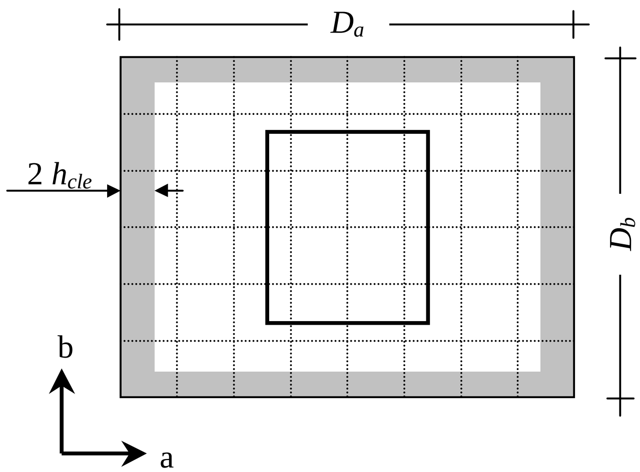

Figure 3.1: Schematic of Floor Area Benefiting from Natural Lighting

This study assumes equal importance of both floor flexibility and comfort level to determine the quality of space for a building. To this end, the maximum and minimum values for floor flexibility and comfort level are found through investigating all possible feasible conceptual designs that can be formed as combinations of the primary design variables given in Table 2.2. These extreme values are then used to normalize all floor flexibilities and comfort levels between 1 and 10, where 1 represents the lowest quality and 10 the highest quality. The normalized floor flexibility and comfort level values for a building are found as,

$$\textit{Floor flexibility} = 1 + 9 \times \frac{CFA - 9}{28} \tag{3.5a}$$

$$\textit{Comfort level} = 1 + 9 \times \frac{\dfrac{4 \times h_{cle} \times (D_a + D_b) - 16 \times h_{cle}{}^2}{D_a \times D_b - C_a \times C_b} \times WIR - 0.05}{0.85} \tag{3.5b}$$

Figure 3.2 demonstrates the normalized floor flexibility vs. comfort level relationships for about six thousands randomly chosen designs. The quality of space for the building is taken to be the product of the floor flexibility and comfort level given by Eqs (3.5), i.e.,

$$Space\ Quality = Floor\ flexibility \times Comfort\ level \tag{3.6}$$

Eq. (3.6) yields bounding values of 3.5 and 37 to define the minimum and maximum quality of space for all possible feasible conceptual designs that can be found through combinations of the primary design variable (alpha-numeric) values given in Table 2.2 (see Figure 3.2).

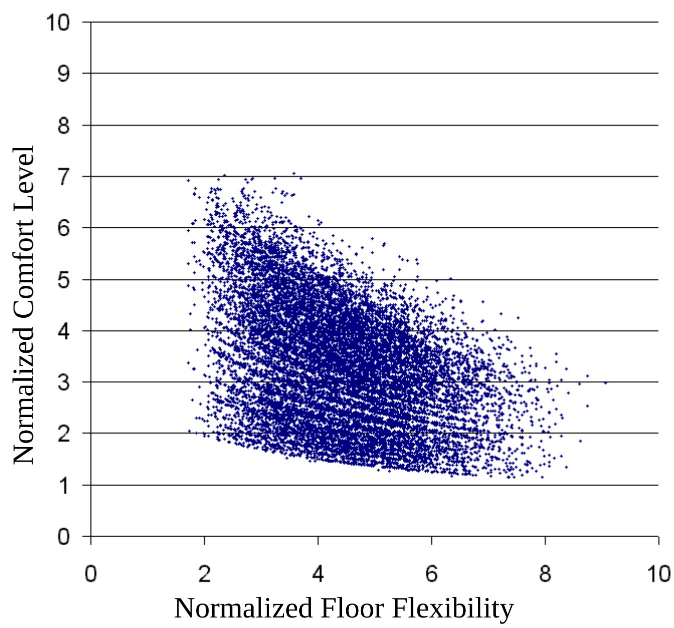

Figure 3.2: Floor Flexibility vs. Comfort Level

3.2.3.2 *Annual Lease Rates*

The lease rate term in Eq (3.4) is a function of the building location and the demand for office space (as defined by industry). The annual lease rate (*LR*) for any given building design is found by a linear mapping between local lease rates and space quality as given by Eq.(3.7), and is given by (see Figure 3.3),

$$LR = LR_{min} + (LR_{max} - LR_{min}) \times \frac{SQ - 3.5}{37 - 3.5} \tag{3.7}$$

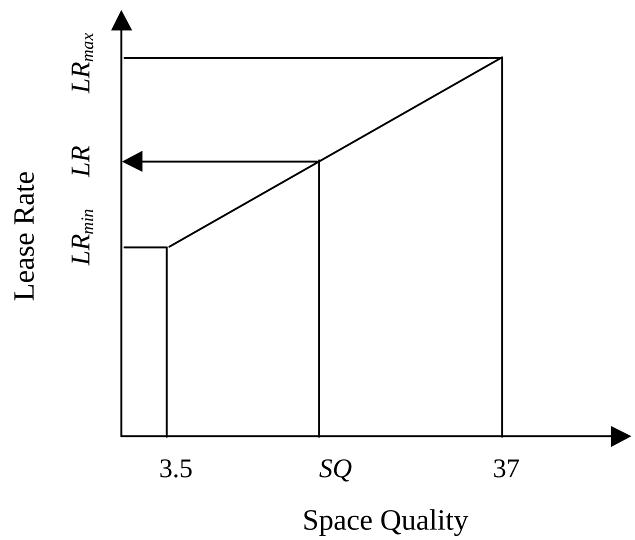

Figure 3.3: Space Quality vs. Lease Rate

3.2.3.3 *Total Annual Revenue Income*

The total rentable floor area and the annual lease rate define the annual revenue income as,

$$Revenue\ Income = RNF \times (D_a \times D_b - C_a \times C_b) \times LR \tag{3.8}$$

where *RNF* is the rentable number of floors, and D_a, D_b, C_a, and C_b are the building and core dimensions in the *a* and *d* directions, respectively. It is noted that assumed in this study is that the occupancy rate does not vary from one design to another and, therefore, that it is reasonable to take revenue income calculated through Eq.(3.8) for an occupancy rate of 100% as the basis to compare different designs. However, in order to establish the potential profitability of each individual design over time it is necessary to account for more realistic occupancy rates that vary over time (see Section 3.3).

Table 3.1: Ranges of Primary Variable Values for the Conceptual Design of Office Buildings

Index	*ST*	*BT*	*CFT*	*SFT*	S_a,S_b (m)	NS_a NS_b	NTS_a, NTS_b (m)	*DCDD*	*CDF*	*WIT*	*WIR* %	*WAT*
0	([1]c) [3]Rigid frame	K&K	Flat plate	Steel joist & beam	4.5	3	2	*a*	0.250	Standard	25	Pre-cast concrete
1	(c)Rigid frame & shear wall	K&X	Flat slab	Com. beam & [5]CIP slab	5.0	4	3	*b*	0.329	Insulated	30	Metal siding panel
2	(c)Framed tube		Slab & beam	W & com. deck & slab	5.5	5	4		0.407	Standard [6]HA	35	Stucco wall
3	([2]s)Rigid Frame		Waffle slab	Com. beam, deck & slab	6.0	6	5		0.486	Insulated HA	40	Glazed panel
4	(s)[4]Frame & bracing				6.5	7			0.564		45	
5	(s)Rigid frame & bracing				7.0	8			0.643		50	
6	(s)Frame & (c)shear wall				7.5	9			0.721		55	
7	(s)Rigid frame & (c)shear wall				8.0	10			0.800		60	
8	(s)Frame, bracing & outriggers				8.5						65	
9	(s)Framed tube				9.0						70	
10					9.5						75	
11					10.0						80	
12					10.5						85	
13					11.0						90	
14					11.5						95	
15					12.0						100	

ST = Structural type (10 choices); *BT*= Bracing type (2 choices); *CFT* = Concrete floor type (4 choices); *SFT* = Steel floor type (4 choices); S_a, S_b = span distances between *columns along the building width a and length b (16 choices in each direction); NS_a, NS_b = number of column bays along the building width a and length b (8 choices in each direction); NTS_a, NTS_b = number of perimeter tube column spans within S_a and S_b; DCDD = direction of the core dimension to be designed first (2 choices); CDF = ratio of the core dimension to the overall length of the building in the same direction (8 choices); WIT= Window type (4 choices); WIR= Window ratio (16 choices); WAT = Wall cladding type (4 choices); [1]c = Concrete; [2] s = Steel; [3] Rigid frame = framework participates in carrying lateral loads; [4] Frame = framework does not participate in carrying lateral loads; [5] CIP = cast-in-place concrete; [6] HA = heat absorbing.*

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Table 3.2: Binary Representation of Primary Design Variables

Base-10 Index	Base 2 Value											
	ST	*BT*	*CFT*	*SFT*	S_a, S_b (m)	NS_a NS_b	NTS_a, NTS_b (m)	*DCDD*	*CDF*	*WIT*	*WIR* %	*WAT*
0	0000	0	00	00	0000	000	00	0	000	00	0000	00
1	0001	1	01	01	0001	001	01	1	001	01	0001	01
2	0010		10	10	0010	010	10		010	10	0010	10
3	0011		11	11	0011	011	11		011	11	0011	11
4	0100				0100	100			100		0100	
5	0101				0101	101			101		0101	
6	0110				0110	110			110		0110	
7	0111				0111	111			111		0111	
8	1000				1000						1000	
9	1001				1001						1001	
10					1010						1010	
11					1011						1011	
12					1100						1100	
13					1101						1101	
14					1110						1110	
15					1111						1111	

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3.2.4 Design Constraints

The implicit and explicit constraints in the conceptual design optimization problem posed by Eqs. (3.1) ensure the feasibility, functionality and performance of the conceptual design. For this study, explicit constraints are imposed on the building footprint dimensions D_a, D_b and height H to satisfy available land restrictions and zoning regulations, on the available lease office space $(D_a \times D_b) - (C_a \times C_b)$ to meet anticipated occupancy demands, on the service core area $C_a \times C_b$ to meet lateral bracing and vertical service requirements, on the distances $D_a - C_a$ and $D_b - C_b$ between the building service core and perimeter to meet horizontal occupancy requirements, and on the building aspect ratio D_a / D_b and slenderness ratio H/D_a (assuming $D_a < D_b$) to ensure that designs are compliant with accepted office space layout principles and structural stability requirements, respectively, i.e.,

$$D_a \leq a_{max} \;\; ; \;\; D_b \leq b_{max} \;\; ; \;\; H \leq H_{max} \tag{3.9a,b,c}$$

$$(D_a \times D_b) - (C_a \times C_b) \geq A_{req} \;\; ; \;\; C_a \times C_b = Percentage(D_a \times D_b) \tag{3.9d,e}$$

$$D_a - C_a \geq 2(CPD_{min}) \;\; ; \;\; D_b - C_b \geq 2(CPD_{min}) \tag{3.9f,g}$$

$$D_a / D_b \geq (D_a / D_b)_{Lower} \;\; ; \;\; H/D_a \leq (H/D_a)^{Upper} \tag{3.9h,i}$$

where a_{max} and b_{max} = maximum allowable building footprint dimensions, H_{max} = maximum height permitted for the building, A_{req} = minimum required lease office space for the building, $Percentage(D_a \times D_b)$ = fixed percentage of building footprint area assigned as service core area, CPD_{min} = specified minimum core-perimeter distance, and $(D_a / D_b)_{Lower}$ = minimum aspect ratio and $(H/D_a)^{Upper}$ = maximum slenderness ratio permitted for the building (assuming $D_a < D_b$).

Implicit constraints are additionally imposed on the conceptual design process by the limits that are placed on the possible values that the primary design variables may take on for an office building. In this regard, Table 3.1 (same as Table 2.2) lists the ranges of possible primary variable values adopted by this study for the design examples presented in Chapter 4; i.e., the conceptual design of an office building may be selected from among 10 different structural types, 2 different bracing types, 4 different floor types for concrete structures, 4 different floor types for steel structures, 4 different window types, 16 different window ratios, 4 different cladding types, a large number of different regular-orthogonal floor plans having from 3 to 10 column bays with span distances of 4.5 to 12 meters in the length and width directions for the building, from 2 to 5 times more column bays on the perimeter of framed tube structures than the interior of the building, and up to 8 different core dimensions in each of the length and width directions for the building.

Further implicit constraints are imposed by rules of good design practice that ensure architectural and structural layouts are feasible and practical. For example, one rule is that there must be at least two columns on each side of the service core for braced structural systems. Other rules ensure that particular types of floor systems are only matched with certain types of structural systems, that particular types of bracing are used in certain places to ensure proper access to the service core area, and that the distances between perimeter tube columns are not too small or too large.

Even though the number of constraints is significant, the typical ranges of variable values for an office building still allow for a large number of viable conceptual designs.

In fact, The data in Table 3.1 allows for more than $11.5x10^{9}$ different conceptual design scenarios (albeit, many are infeasible).

3.2.5 Multi-Criteria Genetic Algorithm (MGA)

A design is Pareto-optimal for the multi-criteria optimization problem posed by Eqs. (3.1) if there exists no other feasible design satisfying Eqs. (3.1b) which dominates it for all three cost-revenue objective criteria. The explicit constraints in Eqs. (3.1b) are defined by Eqs. (3.9), while the implicit constraints are defined by the limits placed on the values of the primary design variables in Table 3.1 and by rules of good design practice. Pareto-optimal design satisfying Eqs. (3.1) define the trade-off relationships between the competing cost-revenue objective criteria.

The problem posed by Eqs. (3.1) is complex and difficult, if not impossible, to solve using procedural-based optimization algorithms that rely on gradient information for solution. On the other hand, the problem is readily solved using adaptive search techniques based on self-learning solution methodologies that do not rely on gradient information. This study applies the adaptive search strategy of a multi-criteria genetic algorithm (MGA) to solve the Pareto optimization problem Eqs. (3.1).

The MGA solves the conceptual design optimization problem using the basic procedures of a conventional GA (see Appendix 3.C). Namely, the genetic operators of selection, crossover and mutation are progressively applied to a population of conceptual designs encoded as binary bit strings until, guided by design fitness evaluations with account for constraint violations, convergence occurs to the Pareto-optimal design set (see Appendix 3.D) after a number of generations.

For any one generation of the genetic search, designs found to violate the constraints Eqs. (3.9) are excluded from the population to ensure that Pareto-optimal designs are identified from among feasible designs alone. The fitness of each feasible design x is based on its (Euclidean) distance $D(x)$ from the nearest Pareto design x^o (Osyczka, 1995), i.e.,

$$D(x) = Min\left[\left(1-\frac{CapitalCost(x)}{CapitalCost(x_j^o)}\right)^2 + \left(1-\frac{OperatingCost(x)}{OperatingCost(x_j^o)}\right)^2 + \left(1-\frac{RevenueIncome(x_j^o)}{RevenueIncome(x)}\right)^2\right]^{0.5} \quad (j=1,2,..,p) \tag{3.10}$$

where $D(x) > 0$ for each non-Pareto design x, while $D(x_j^o) = 0$ for each of the j = 1,2,..,p Pareto designs x_j^o. The fitness of each design x is calculated as,

$$F(x) = F_{max} - D(x) \tag{3.11}$$

where, to ensure that Eq. (3.11) does not produce a negative fitness for any design, F_{max} = the maximum $D(x)$ value found for Eq. (3.10) from among all feasible designs for the current generation. Note from Eqs. (3.10) and (3.11) that $F(x_j^o) = F_{max}$ for each Pareto design x_j^o, while that for each non-Pareto design x lies somewhere in the range $0 \leq F(x) < F_{max}$ depending on its distance from the Pareto-optimal set.

Having the fitness of all designs in the current generation, this study uses roulette wheel selection, two-point crossover and single-bit mutation (see Appendix 3.C) to identify the next generation of feasible designs. An elitist strategy is employed to ensure that current Pareto designs survive into the next generation, where they then compete with all other newly created feasible designs to become members of the new Pareto-optimal set. The genetic search procedure is repeated until there is no change in the Pareto set for a pre-assigned number of consecutive generations, at which point the MGA is deemed to have converged to the optimal Pareto set.

3.2.6 Design Computational Procedure

The flow chart for a single run of the multi-criteria genetic algorithm for Pareto-optimal conceptual design of an office building is shown in Figure 3.4. To begin, the building design project is specified by the information and limitations defined by the parameters for the design (e.g., see Table 4.1), by the ranges of possible values of the primary design variables (see Table 3.1), by the values of the lower and upper bounds for the constraint Eqs.(3.9) controlling the secondary design variables (e.g., see Table 4.1), and by rules of good design practice (e.g., see the following). As well, to facilitate the genetic search, values are assigned for population size and crossover and mutation probabilities (e.g., see Examples in Chapter 4).

Each member of the initial genetic population is a randomly generated string of binary (base-2) values of the primary design variables which, when decoded to their base-10 index values, define the structure and floor systems, the cladding and window types, the window ratio, and the numbers of column bays and corresponding span distances in the width and length directions for a particular conceptual design of the building. For example, from Table 3.2 (the binary representation of the primary variable values in Table 3.1), the 39-bit binary string 0011|0|10|11|1010|0111|101|011|01|10|1|100|10|1001|11 decodes to the base-10 indices 3,0,2,3,10,7,5,3,1,2,1,4,2,9,3 which, from Table 3.1, identify: structural type = *ST* = steel rigid frame; bracing type = *BT* = K&K; concrete floor type = *CFT* = two-way slab and beam; steel floor type = *SFT* = composite beam,

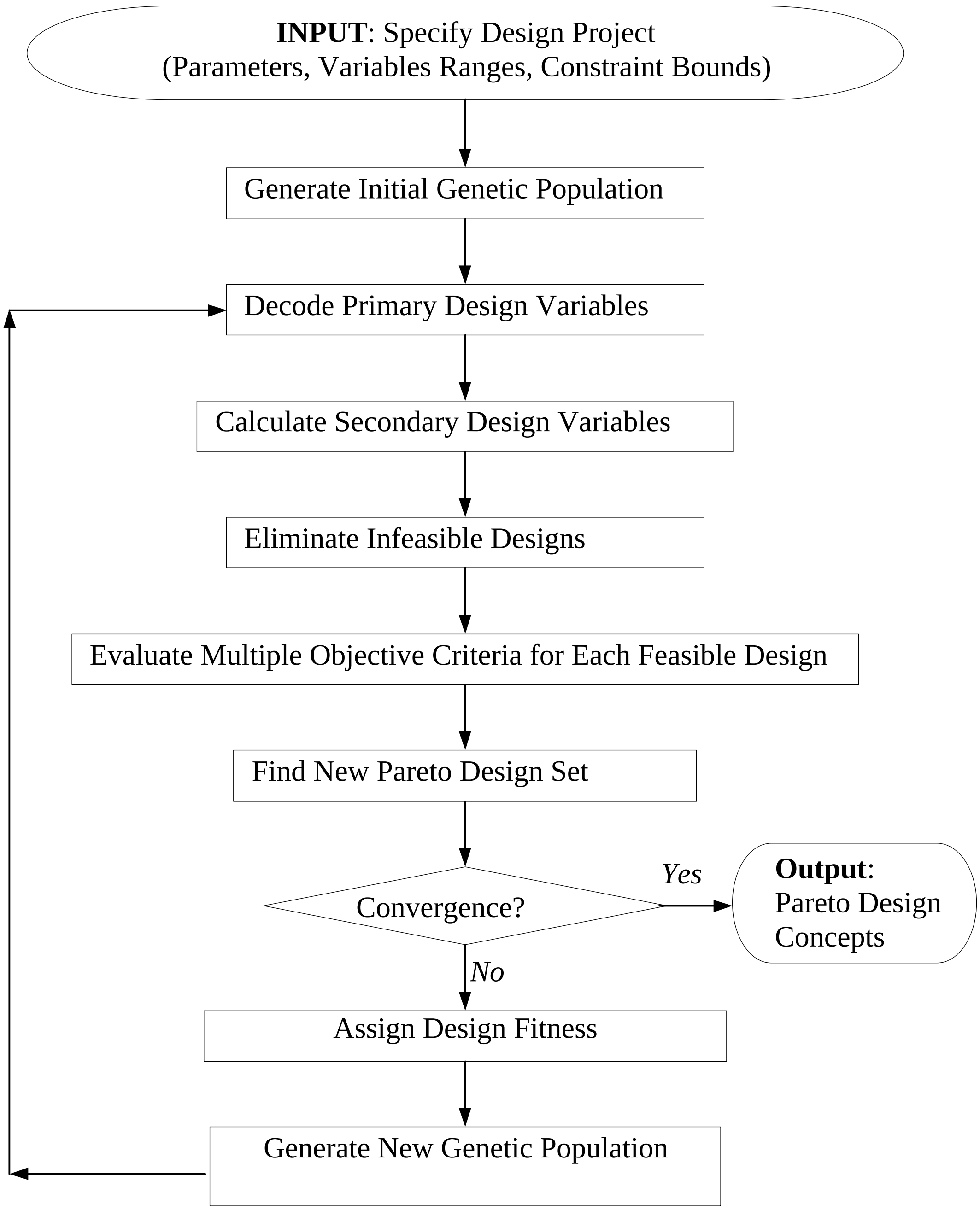

Figure 3.4: Conceptual Design Computational Procedure

deck and concrete slab; span distances between columns along the building width $a = S_a$ = 9.5m; span distances between columns along the building length $b = S_b$ = 8.0m; number of column spans along the building width $a = NS_a$ = 8; number of columns spans along the building length $b = NS_b$ = 6; number of perimeter tube column spans within S_a = NTS_a = 3; number of perimeter tube column spans within $S_b = NTS_b$ = 4; direction of the core dimension to be assigned first = *DCDD* = *b;* ratio of the core dimension in the *b* direction to the overall dimension of the building in the *b* direction = *CDF* = 0.564; window type = *WIT* = standard heat absorbing; window ratio = *WIR* = 70%; and wall cladding type = *WAT* = glazed panel.

Rules of good design practice are then invoked for each design scenario to exclude any primary variables values that are not applicable for the chosen structure type. For the foregoing design scenario, for example, since the structural type is a steel rigid frame, the values for the variables *BT*, *CFT*, *NTSa*, and *NTSb* are deemed not applicable and are excluded from further consideration for the design. As another example, if the design is such that the structural type = *ST* = steel frame and bracing, the bracing is always selected to be either K-bracing on all four sides of the service core or K-bracing on the two sides of the core having the larger bay widths and X-bracing on the two sides having the smaller bay widths, but never X-bracing on the sides having the larger bay widths because this would then prevent ready access to elevators and stairways in the core area.

Having the values of the applicable primary design variables for a particular conceptual design of the building, the corresponding values of the secondary design variables are found to establish the dimensions of the building footprint and service core, the number of stories, the available lease office space, the floor depth, the building height, and the aspect and slenderness ratios for the building. For example, from the foregoing, the building footprint dimensions are found as $D_a = NS_a \times S_a = 8 \text{ x } 9.5 = 76.0$m, and $D_b = NS_b \times S_b = 6 \text{ x } 8.0 = 48.0$m. The service core area is found as a specified percentage of the footprint area = $D_a \times D_b = 76.0 \text{ x } 48.0 = 3648\text{m}^2$. For example, for $Percentage = 20\%$, the core area is $C_a \times C_b = 0.20 \text{ x } 3648 = 729.6\text{m}^2$. Knowing the fraction that one service core dimension is to be of the footprint dimension in the same direction, the other core dimension is calculated to meet the required service core area. For example, from the foregoing, for the core width dimension randomly selected to be $C_b = 0.564\, D_b = 0.564 \text{ x } 48.0 = 26.51$m, the core length dimension $C_a = 729.6 / 26.51 = 27.50$m. The number of stories is found to meet the minimum lease office space required for the building. For example, for $A_{req} = 60{,}000\text{m}^2$, the available lease office space per floor = 3648 - 729.6 = 2918.4 m^2, and the number of mechanical taken to be 4% of the number of rentable floors, the number of rentable floors = $NRF = 60{,}000 / 2918.4 = 20.55 = 21$, the number of mechanical floors $NMF = NRF \times 0.04 = 21 \text{ x } 0.04 = 0.84 = 1$, and the total number of floors $NF = NRF + NMF = 21 + 1 = 22$. The actual total amount of available rental/lease space = 21 x 2918.4 = 61,286m^2. For initial calculations, the floor depth is considered common for all stories and is defined by the type of floor and the bay area. For example, from the foregoing, for SFT = composite beam, deck and concrete slab, and bay area = $S_a \times S_b = 9.5 \text{ x } 8.0 = 76.0\text{m}^2$, the depth of floor = $DF = 0.63$m from Table 3.A.3b. The height of the building is defined by the number of floors NF, the floor depth DF, the specified floor-to-ceiling clearance height and the depth of false ceiling. For example, for 3m clearance height and 0.5m false ceiling depth common for all 22 stories, the overall building height $H = 22 \text{ x } (3 + 0.63 + 0.5) = 90.86$m. The building aspect ratio D_b / D_a = 48.0 /76.0 = 0.63, while the slenderness ratio = H /D_b = 90.86 /48.0 = 1.89.

Designs which violate any of the constraint Eqs. (3.9) concerning plan and height restrictions, office space requirements, and appropriate aspect and slenderness ratios for the building, are deemed infeasible and eliminated from the population of conceptual designs, as are any building concepts not in keeping with the rules of good design practice (e.g., tube structures with spans between perimeter columns smaller than 2.25m and larger than 4.25m would be eliminated because those particular structural layouts are not practical). Eliminated designs are replaced by other, randomly generated, feasible designs so as to maintain a fixed population size.

The capital cost, operating cost and income revenue for each feasible conceptual design are calculated as described in Chapter 3 and related Appendices 3.A and 3.B. Having the cost and revenue values for the entire population of feasible conceptual designs for the building, the Pareto-optimal design set is formed by those designs that each have the characteristic that there is no other design in the population that completely dominates it in the sense of having both smaller capital and operating costs and larger income revenue.

Having the Pareto-optimal design set, the fitness of each design in the population is calculated through Eqs. (3.10) and (3.11). Then, while invoking an elitist strategy to retain the binary strings defining the Pareto-optimal designs (Figure 3.5), the genetic operations of reproduction, crossover and mutation are carried out to create a new population of binary design representations to commence the next generation of the genetic search.

Convergence of a single run of the multi-criteria genetic algorithm occurs when the Pareto-optimal design set is found to remain (relatively) the same for a specified number of consecutive generations and no improvement is noticed in the values of the cost-revenue objective criteria. Multiple runs of the MGA starting from different initial genetic populations are conducted, and the Pareto-optimal sets found at convergence of the different runs are combined together to form the overall Pareto-optimal design set (e.g., see Examples in Chapter 4).

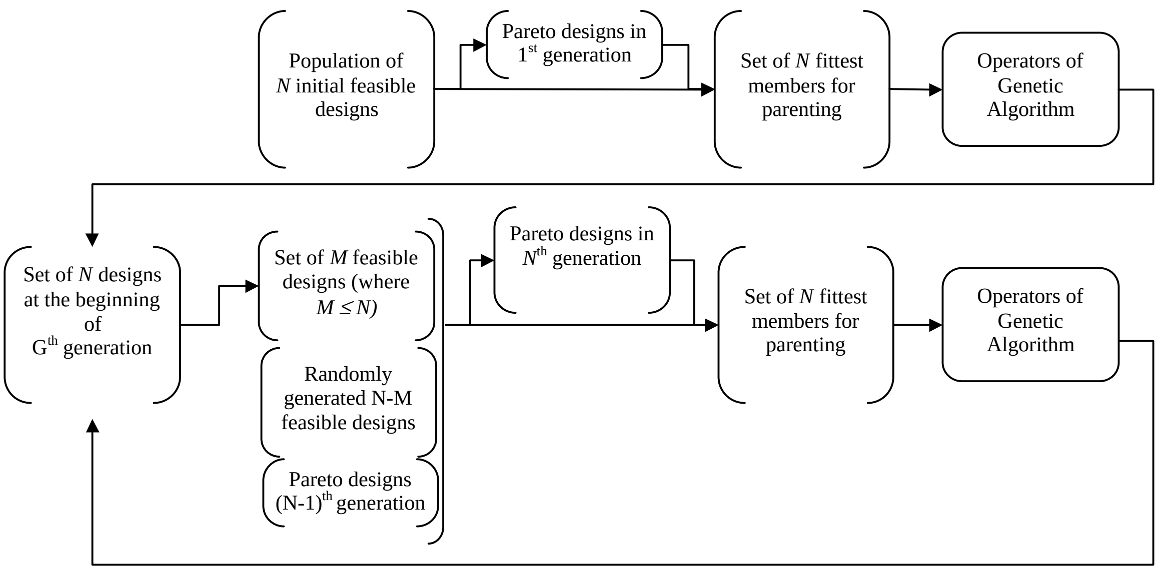

Figure 3.5: Elitist Strategy for Multi-criteria Genetic Algorithm

3.2.7 Design Profitability

It should be noted that the cost-revenue criteria evaluated for the genetic search described in the foregoing do not account for inflation and mortgage interest rates because such life-cycle costing does not affect the Pareto optimality of a building design. Once the Pareto-optimal design set has been found, the combined cost-revenue function described in the following (which does account for life-cycle inflation and mortgage interest rates) can then be applied to assess the potential profitability of each Pareto-optimal building design over time.

The profit potential of a building design over time is assessed using life-cycle costing analysis to estimate cash flows on an annual basis after completion of the project construction phase. To this end, this study assumes that the building occupancy rates vary in time as shown in Table 3.3.

Table 3.3: Variable Occupancy Rates

Time	Occupancy Rate (OR)
Throughout Year 1	50% leased
Throughout Year 2	70% leased
Throughout Year 3	85% leased
Year 4 and after	95% leased

The potential profitability of a building design can be assessed by evaluating the following cost-revenue function,

$$\begin{aligned} \mathit{Profitability} = & \left(RI \sum_{k=1}^{n} OR_k (1+MR)^{n-k} (1+IR)^{k-1}\right) \\ & - \left(OC\left(\sum_{k=1}^{n} (1+MR)^{n-k} (1+IR)^{k-1}\right)\right) \\ & - \left(CC\,(1+MR)^{n}\right) \end{aligned} \tag{3.12}$$

where: the values of CC (capital cost), OC (operating cost) and RI (revenue income) are found through Eqs. (3.2), (3.3) and (3.4) for the building design; MR (mortgage rate) and IR (inflation rate) are fixed annual life-cycle rates; k = a yearly counter; OR_k = occupancy rate (Table 3.3); and n = the number of years after completion of construction. If $Profitability > 0$ from Eq. (3.12), the design is profitable in year n and all years thereafter; otherwise, if $Profitability < 0$ the design is not profitable in year n or in any year previous. As illustrated for the design examples, in Chapter 4, Eq. (3.12) can also be used to predict the year n in which a building design first becomes profitable.

Appendix 3.A - Capital Cost (Eq. 3.2)

3.A.1 Cost of Land

The land cost is a function of unit land rates (as defined by local location information) and the footprint dimensions of the building, i.e.,

$$Cost_{Land} = (D_a \times D_b) \times Land_{unit\ cost} \qquad (3.A.1)$$

3.A.2 Cost of Floor System

For known column layout, floor system, and applied live and dead gravity loads, the cost, depth and selfweight of the floor system per unit area are found using prepared databases based on bay area. For structural systems that do not engage the flooring system as part of the lateral load resisting system, such as tubes, the floor system is usually designed only for gravity loading (the databases used for floor systems in this study are generated based on this condition).

Table 3.A.1 defines the gravity loading considered by this study. Table 3.A.2a and 3.A.2b identify the percentage costs of different components of floor system construction. Tables 3.A.3a and 3.A.3b represent the cost, depth and selfweight of different concrete and steel floor systems under gravity loads, for bay areas up to 149 m^2.

Table 3.A.1: The Intensity of Applied Gravity Loads

Load	**Intensity (kN/m^2)**
Live load	2.80
Self weight	Depends on type of floor and bay area; see Tables 3.A.3a & 3.A.3b
Superimposed Dead Load	
Partitions	1.00
Plumbing and ducting	0.20
False ceiling and fixtures	0.15
Floor finishing	0.10
Total	1.45

Table 3.A.2: Percentage of Different Construction Components in Floor Unit Cost

Floor Type	**Average percentage of the unit cost**			
	Forming %	Reinforcement %	Concrete %	Structural Steel %
Flat plate	50	20	30	-
Flat slab	51	19	30	-
Beam and slab	54	21	25	-
Waffle slab	54	18	28	-

(a) Concrete Structures

Floor Type	**Average percentage of the unit cost**			
	Forming %	Reinforcement %	Concrete %	Structural Steel %
Steel joist & beams with deck and slab	-	5	20	75
Com. Beam & CIP Slab	41	6	15	38
W Shape Com. Beam Deck & Slab	-	3	16	81
Composite beam, deck and slab	-	3	26	71

(b) Steel Structures

Table 3.A.3: Floor Information

Bay Area (m^2)	**Flat Plate** Cost $\$/m^2$	Depth m	Self W kN/m^2	**Flat Slab** Cost $\$/m^2$	Depth m	Self W kN/m^2	**Beam & Slab** Cost $\$/m^2$	Depth m	Self W kN/m^2	**Waffle Slab** Cost $\$/m^2$	Depth m	Self W kN/m^2
21	85.36	0.14	3.29	92.35	0.22	3.73	101.61	0.22	3.25	110.44	0.25	4.97
28	94.18	0.19	4.49	97.41	0.27	4.16	111.73	0.29	4.01	113.02	0.25	4.97
37	94.40	0.19	4.78	100.75	0.28	4.44	117.33	0.29	4.40	115.60	0.25	4.97
46	100.21	0.23	5.40	109.04	0.37	5.21	126.91	0.36	5.07	117.43	0.25	5.07
58	104.73	0.24	5.69	110.87	0.39	5.54	126.26	0.36	5.26	120.88	0.30	5.26
70	109.25	0.25	5.98	118.19	0.42	6.12	131.64	0.43	6.02	122.39	0.30	5.45
84	113.77	0.27	6.26	123.57	0.46	6.79	141.65	0.43	6.55	126.80	0.36	6.17
98	118.30	0.28	6.55	131.32	0.52	7.46	147.47	0.51	7.17	126.15	0.36	6.17
114	122.82	0.29	6.84	134.55	0.58	7.89	152.31	0.51	7.56	134.55	0.36	6.41
130	127.34	0.31	7.12	139.93	0.65	8.32	159.31	0.58	8.23	139.39	0.41	6.50
149	131.86	0.32	7.41	150.69	0.71	8.75	166.30	0.65	8.90	143.70	0.41	6.50

(a) Concrete Structures

Bay Area (m^2)	**Steel Joist & Beam Deck & Slab** Cost $\$/m^2$	Depth m	Self W kN/m^2	**Com. Beam & CIP Slab** Cost $\$/m^2$	Depth m	Self W kN/m^2	**W Shape Com. Beam Deck & Slab** Cost $\$/m^2$	Depth m	Self W kN/m^2	**Com. Beam, Deck & Slab** Cost $\$/m^2$	Depth m	Self W kN/m^2
21	77.93	0.48	2.05	118.40	0.53	2.62	112.70	0.41	2.10	100.97	0.58	1.67
28	84.28	0.48	2.10	125.40	0.53	2.62	121.85	0.41	2.10	103.76	0.58	1.67
37	90.63	0.66	2.10	132.40	0.53	2.62	131.00	0.53	2.43	106.56	0.58	1.91
46	95.58	0.66	2.15	139.39	0.53	2.62	144.24	0.53	2.48	109.36	0.60	1.91
58	104.41	0.66	2.15	146.39	0.57	2.91	149.08	0.74	2.53	112.16	0.60	2.05
70	106.78	0.74	2.15	154.46	0.57	2.91	159.31	0.74	2.58	112.50	0.60	2.10
84	114.21	0.81	2.15	152.85	0.63	2.67	163.61	0.74	2.58	112.59	0.67	1.95
98	126.91	0.81	2.19	165.23	0.71	3.06	174.38	0.89	2.67	117.54	0.75	2.00
114	135.95	0.97	2.19	167.92	0.71	2.77	179.22	0.89	2.67	128.74	0.75	2.19
130	144.99	1.08	2.24	177.60	0.71	2.82	186.22	0.97	2.67	134.87	0.75	2.19
149	154.03	1.27	2.24	187.29	0.71	2.82	193.21	1.04	2.72	141.01	0.75	2.38

(b) Steel Structures

** Prices shown are calculated based on US national average costs. For bay areas different from those listed, the cost, depth and selfweight are interpolated or extrapolated.*

The cost of the floor system is the product of the unit cost of floor system times the built floor area including the area covered by elevators and stair cases, i.e.,

$$Cost_{Floor} = NF\,(D_a \times D_b - (NSC \times OILSC \times OIWSC - NE \times 5.9)) \times Floor_{Unit\ Cost} \quad (3.A.2)$$

For any given type of floor, the unit cost accounts for the cost of the different construction components (i.e., steel, concrete, reinforcement, forming), which can be established as the product of their percentage cost share (Table 3.A.2) times the floor unit cost (Table 3.A.3). The US national average floor unit cost in Table 3.A.3 can be modified for any specific location (city) by accounting for the different cost location factors that relate the cost of different materials to their US national average cost (see Table 2.1). As well, the US national average costs of the individual components can also be modified to account for the building location (city). For an example, the cost of components of a flat plate flooring system are: $Cost_{forming} = 0.50 \times Floor_{unit\ cost}$; $Cost_{reinforcement} = 0.20 \times Floor_{unit\ cost}$; $Cost_{concrete} = 0.30 \times Floor_{unit\ cost}$; and $Cost_{steel} = 0.00 \times Floor_{unit\ cost}$. Therefore, the modified floor unit cost is found as:

$$\begin{aligned} Mod.\ Floor_{unit\ cost} = (&Cost_{forming} \times FCLF + Cost_{reinforcement} \times RCLF + \\ &Cost_{concrete} \times CCLF + Cost_{steel} \times SCLF) \end{aligned} \quad (3.A.3)$$

where $FCLF$, $RCLF$, $CCLF$ and $SCLF$ are cost location factors for forming, reinforcement, concrete and steel, respectively (Table 2.1).

The data in Table 3.A.3 can also be used for structural systems that take advantage of the flooring system to resist lateral loads. This is done by choosing a larger bay area than reality such that the gravity loading induces moments in the floor that are approximately equivalent to those that would be caused by a combination of gravity and lateral loads. For these types of structural systems where floors contribute to lateral stiffness, this study changes the size of the flooring system every four floors to account for the increased forces induced in the flooring system over the height of the building. Hence, contrary to that for structural systems that do not rely on floor elements to carry lateral forces, the cost of the flooring system is not constant for all stories of the building for these structural systems.

3.A.3 Cost of Columns

In order to achieve a fair estimate of the cost of columns in a building at the conceptual stage of the design, it is necessary to find a reasonably accurate approximation of the column sizes necessary to resist the axial forces induced by the different design load combinations. This approximation should account for both dead and live gravity loads in addition to applied lateral loads. In this study, estimated axial forces in columns are found from the results of approximate determinate analysis for different combinations of gravity dead and live floor loadings, and from the results of approximate indeterminate analysis (Portal Method) for applied lateral loads (Smith and Coull 1991). Additional axial forces induced in perimeter columns by vertical bracing systems and outrigger trusses are also accounted for.

Having the factored axial forces, the column sizes are found based on the Handbook of Steel Construction (1997) and the Concrete Design Handbook (1995). For the purpose of choosing appropriate sizes, it is assumed that columns are four meter (4m) tall on average. Tables 3.A.4 and 3.A.5 represent the sections, dimensions and costs adopted by this study for steel and concrete columns, respectively. Figures 3.A.1, 3.A.2, 3.A.3 and 3.A.4 demonstrate the relationships between factored axial resistance and material mass, area and volume for steel and concrete columns (based on the Canadian design standards: Concrete Design Handbook 1995 and Handbook of Steel Construction 1997). These Tables and Figures are based on the following material properties for steel and concrete: yield stress of structural steel F_y = 350 MPa; compressive strength of concrete f'_c = 400MPa; yield stress of reinforcement steel f_y = 400 MPa.

Table 3.A.4: Steel Column Costs

Designation	[1]FR (kN)	[2]CSA mm²	Mass/[3]vlm kg/m	Cost[4] $/m	Designation	[1]FR (kN)	[2]CSA mm²	Mass/[3]vlm Kg/m	[4]Cost $/m	Designation	[1]FR (kN)	[2]CSA mm²	Mass/[3]vlm Kg/m	[4]Cost $/m
WWF650-864	34500	110000	858.00	1750.32	WWF450-342	13600	43600	340.08	693.76	W310-179	5770	22800	177.84	362.79
WWF600-793	31700	101000	787.80	1607.11	WWF500-306	12200	39000	304.20	620.57	WWF350-137	5300	17500	136.50	278.46
WWF650-739	29600	94100	733.98	1497.32	WWF400-303	11900	38600	301.08	614.20	W310-158	5040	20000	156.00	318.24
WWF550-721	28800	92000	717.60	1463.90	WWF500-276	11000	35200	274.56	560.10	W310-143	4580	18200	141.96	289.60
WWF600-680	27200	86600	675.48	1377.98	WWF450-274	10900	35000	273.00	556.92	W310-129	4130	16500	128.70	262.55
WWF500-651	25900	83000	647.40	1320.70	WWF400-273	10700	34800	271.44	553.74	W310-118	3750	15000	117.00	238.68
WWF550-620	24800	79100	616.98	1258.64	WWF350-263	10200	33600	262.08	534.64	W310-107	3390	13600	106.08	216.40
WWF650-598	23900	76200	594.36	1212.49	WWF500-254	10100	32300	251.94	513.96	W310-97	3060	12300	95.94	195.72
WWF500-561	22400	71600	558.48	1139.30	WWF450-248	9820	31600	246.48	502.82	W310-86	2420	11000	85.80	175.03
WWF600-551	22000	70200	547.56	1117.02	WWF400-243	9540	31000	241.80	493.27	W310-79	2180	10000	78.00	159.12
WWF550-503	20100	64200	500.76	1021.55	WWF350-238	9180	30200	235.56	480.54	W250-73	2060	9280	72.38	147.66
WWF650-499	20000	63600	496.08	1012.00	WWF450-228	9000	29000	226.20	461.45	W310-67	1470	8500	66.30	135.25
WWF600-460	18400	58600	457.08	932.44	WWF400-220	8620	28000	218.40	445.54	W200-59	1380	7530	58.73	119.82
WWF500-456	18200	58200	453.96	926.08	WWF350-212	8150	27000	210.60	429.62	W250-58	1320	7420	57.88	118.07
WWF400-444	17500	56600	441.48	900.62	WWF450-201	7950	25600	199.68	407.35	W200-52	1210	6620	51.64	105.34
WWF550-420	16800	53600	418.08	852.88	WWF350-192	7390	24400	190.32	388.25	W250-49	1080	6250	48.75	99.45
WWF450-409	16300	52200	407.16	830.61	W310-226	7380	28900	225.42	459.86	W200-46	1050	5820	45.40	92.61
WWF650-400	15500	51000	397.80	811.51	WWF400-178	6980	22700	177.06	361.20	W200-42	737	5280	41.18	84.02
WWF500-381	15200	48600	379.08	773.32	WWF350-176	6770	22400	174.72	356.43	W200-36	627	4540	35.41	72.24
WWF600-369	14700	47000	366.60	747.86	W310-202	6550	25800	201.24	410.53	W150-30	477	3790	29.56	60.31
WWF400-362	14300	46200	360.36	735.13	WWF400-157	6190	20100	156.78	319.83	W150-22	339	2840	22.15	45.19
WWF500-343	13700	43800	341.64	696.95	WWF350-155	5980	19800	154.44	315.06					

[1] *Factored Resistance,* [2] *Cross Section Area,* [3] *vertical linear meter,*[4] *Prices shown are calculated based on US national average costs (for specific locations, the cost of steel is adjusted accordingly).*

Table 3.A.5: Concrete Column Costs

Width (m)	[1]CSA (m^2)	[2]L (m)	[3]FA (m^2)	[4] LS %	[5]EXS %	Reinforcement (1000kg)/[6] vlm	Concrete Volume (m^3/ vlm)	[7] FR (kN)	[8] Form Cost $/vlm	[8] Concrete Cost $/vlm	[8] Steel Cost $/vlm
0.25	0.065	15.50	1.02	4.3	1	0.027	0.065	1517	46.84	9.26	38.22
0.3	0.093	10.76	1.22	3.9	1	0.035	0.093	2072	56.21	13.33	50.67
0.36	0.126	7.91	1.42	3.8	1	0.047	0.126	2795	65.57	18.15	67.84
0.41	0.165	6.05	1.63	4.0	1	0.064	0.165	3736	74.94	23.70	92.30
0.46	0.209	4.78	1.83	4.0	1	0.082	0.209	4741	84.31	30.00	117.06
0.51	0.258	3.88	2.03	3.9	1	0.098	0.258	5756	93.68	37.04	140.76
0.56	0.312	3.20	2.24	4.0	1	0.122	0.312	6939	103.04	44.82	174.51
0.61	0.372	2.69	2.44	4.0	1	0.146	0.372	8445	112.41	53.33	209.34
0.66	0.436	2.29	2.64	3.9	1	0.167	0.436	9754	121.78	62.59	238.86
0.71	0.506	1.98	2.84	4.0	1	0.195	0.506	11386	131.15	72.59	279.85
0.76	0.581	1.72	3.05	3.9	1	0.220	0.581	12926	140.51	83.33	315.42
0.81	0.661	1.51	3.25	4.0	1	0.259	0.661	15000	149.88	94.82	370.69
0.86	0.746	1.34	3.45	4.0	1	0.292	0.746	16930	159.25	107.04	418.48
0.91	0.836	1.20	3.66	4.1	1	0.331	0.836	19057	168.62	120.00	473.83
0.97	0.932	1.07	3.86	4.1	1	0.369	0.932	21269	177.98	133.70	528.98
1.02	1.032	0.97	4.06	4.1	1	0.408	1.032	23545	187.35	148.15	584.97
1.07	1.138	0.88	4.27	4.0	1	0.439	1.138	25624	196.72	163.33	629.67
1.12	1.249	0.80	4.47	4.1	1	0.495	1.249	28547	206.09	179.26	709.21
1.17	1.365	0.73	4.67	4.0	1	0.528	1.365	30725	215.45	195.93	756.84
1.22	1.486	0.67	4.88	4.0	1	0.584	1.486	33774	224.82	213.34	837.38
1.27	1.613	0.62	5.08	4.0	1	0.633	1.613	36626	234.19	231.48	906.81
1.32	1.745	0.57	5.28	4.0	1	0.682	1.745	39543	243.56	250.37	976.91
1.37	1.881	0.53	5.49	4.0	1	0.731	1.881	42522	252.92	270.00	1047.19
1.42	2.023	0.49	5.69	4.0	1	0.783	2.023	45531	262.29	290.37	1121.67
1.47	2.17	0.46	5.89	3.9	1	0.833	2.170	48637	271.66	311.48	1193.52
1.52	2.323	0.43	6.10	4.1	1	0.922	2.323	53106	281.03	333.34	1321.38

[1]Cross Section Area,[2]Length of a column for one cubic meter volume,[3] Forming Area for one meter of the column, [4] Longitudinal Steel percentage,[5] EXtra Steel percentage for ties and over laps, [6] vertical linear meter, [7] Factored Resistance, [8] Prices shown are calculated based on US national average costs(for specific locations, the costs of reinforcement, concrete and forming are adjusted accordingly).

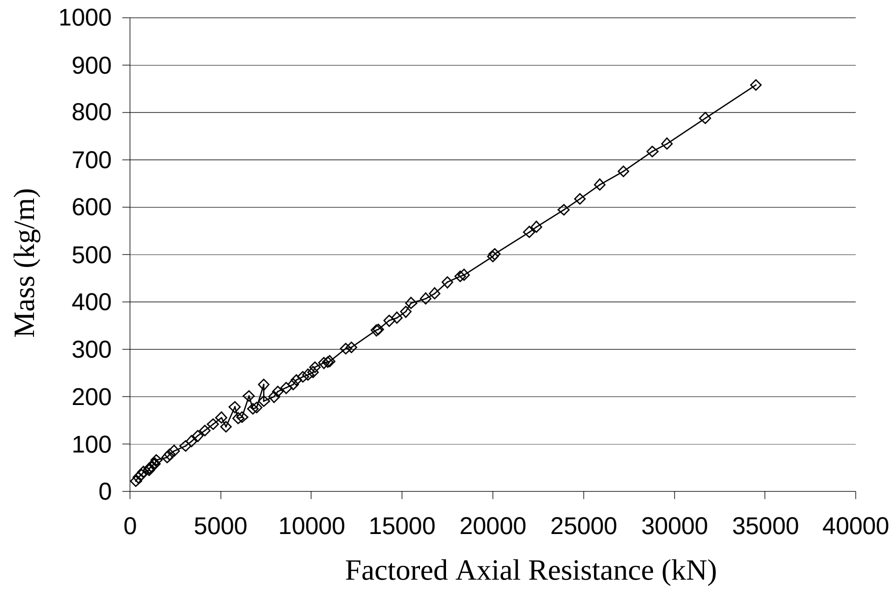

Figure 3.A.1: Mass of Steel Columns vs. Axial Load Capacity

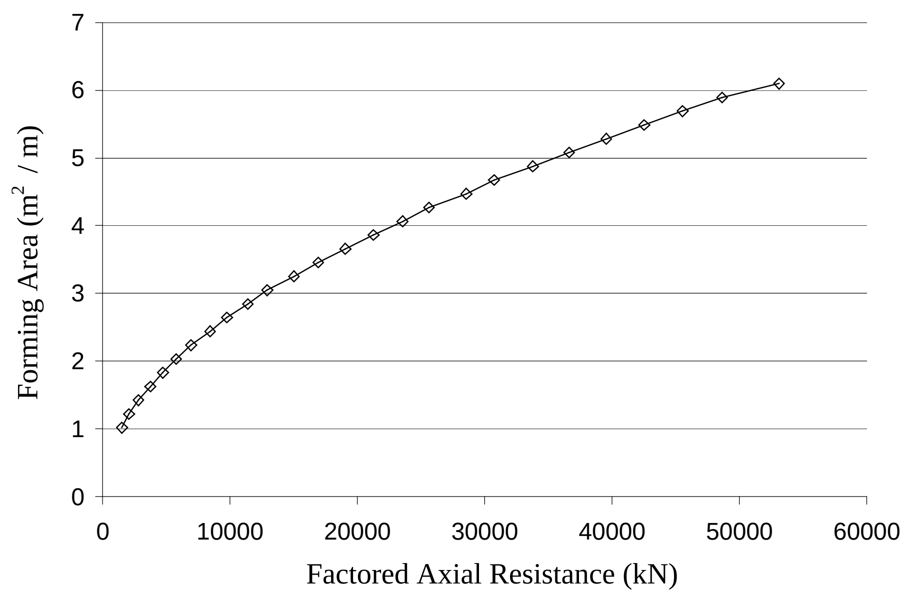

Figure 3.A.2: Forming Area vs. Axial Load Capacity of Concrete Columns

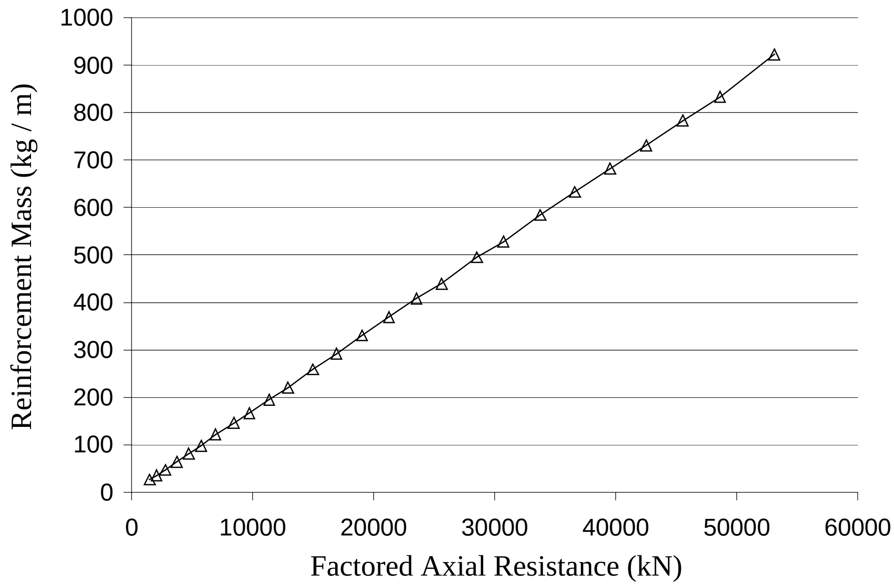

Figure 3.A.3: Reinforcement Mass vs. Axial Load Capacity of Concrete Columns

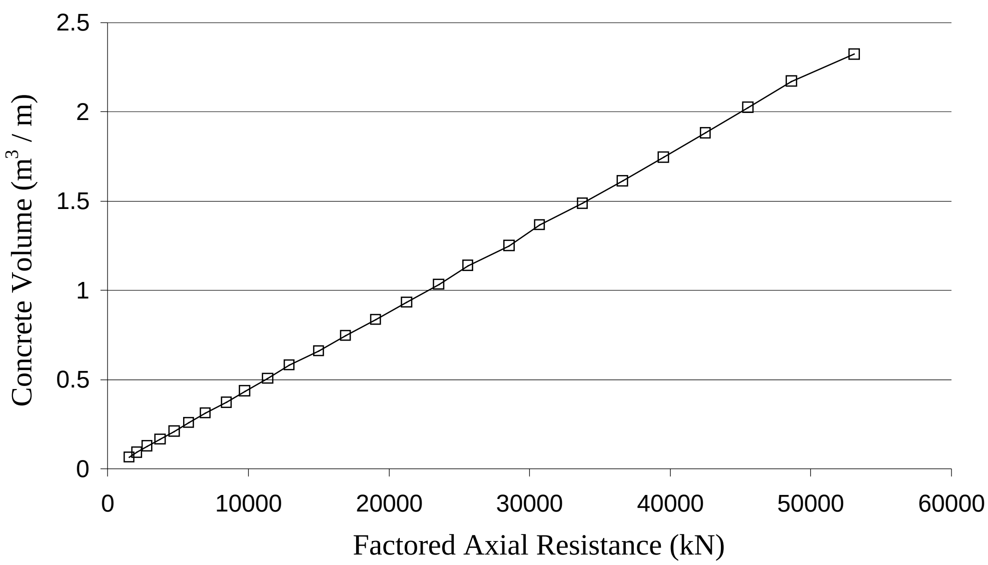

Figure 3.A.4: Concrete Volume vs. Axial Load Capacity of Concrete Columns

Having the cost of each column per vertical linear meter, the cost of columns is found as,

$$Cost_{\,Steel\ columns} = HF \times \sum_{j=1}^{NF}\sum_{i=1}^{nc} Col_{mass\,/\,vlm} \times SCLF \times Steel_{unit\,cost} \tag{3.A.4}$$

$$\begin{aligned} Cost_{\,Concrete\ columns} = HF \times \sum_{j=1}^{NF}\sum_{\mathrm{i}=1}^{\mathrm{nc}} \; & (Rebar_{\,mass/vlm} \times RCLF \times Rebar_{\,unit\ cost} + \\ & Concrete_{\,volume\ vlm} \times CCLF \times Concrete_{\,unit\ cost} + \\ & Forming_{\,area\ vlm} \times FCLF \times Forming_{\,unit\ cost}) \end{aligned} \tag{3.A.5}$$

where $Col_{mass/vlm}$ is the mass of each column per vertical linear meter, nc is the number of columns, NF and HF are the number and height of floors, and $SCLF$, $CCLF$, $RCLF$ and $FCLF$ are the cost location factors for steel, concrete, reinforcement and forming, respectively. The mass of reinforcement, volume of the concrete and area of forming in Eq. (3.A.5) are each for one meter length of the column. While forces in columns change from one story to the next, columns sizes are held constant over four stories by designing for the column forces in the lowest of the four stories.

3.A.4 Cost of Lateral Load Resisting System

For structural systems that carry lateral forces using only column and floor systems, the cost of the lateral load resisting system is already accounted for since choosing appropriate column and floor sizes accounts for worse-case gravity and lateral load combinations. However, for systems relying on additional means for lateral stability, such as shear walls, bracings, outrigger trusses and tubes, approximate indeterminate analysis (e.g., Portal Method) for lateral loads is used to estimate forces and, hence, sizes for these additional structural elements. Having the sizes, the cost of the lateral load resisting system is then found.

To achieve a feasible structural layout of lateral load resisting systems, it is assumed that there are at least two columns within the core area in both the a and b directions for systems that involve shear walls or bracings. The shear walls and bracings are placed in the core area in a symmetrical arrangement aligned with the axes of the column rows (Figure 3.A.5). When bracing is used, K-bracing is placed in the direction having the largest span distance between columns so as to provide appropriate openings for access to the area within the structural core, and either K or X-bracing is used in the other direction. To ensure access to the entire floor plan on floors that contain outrigger trusses, only K-trusses are used to transfer load to the exterior columns.

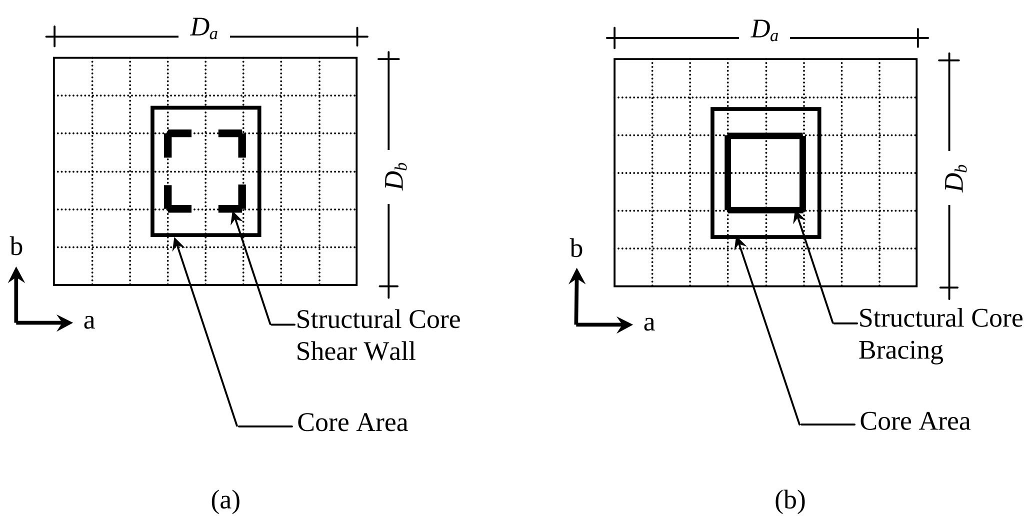

Figure 3.A.5: Schematic of Location of Structural Core within the Core Area

Hollow tubular sections are considered for both compression and tension members (Table 3.6) in designing vertical and outrigger truss systems. Having the size and mass of individual members, the cost of the bracing system is given by the sum of the costs of all members as,

$$Cost_{Bracing} = \sum_{j=1}^{NF}\sum_{\mathrm{i}=1}^{\mathrm{nbm}} BraM_{ij} \times lbm_{ij} \times SCLF \times Steel_{unit\ cost} \tag{3.A.6}$$

where $BraM_{ij}$ is the mass per meter of bracing member i in story j, lbm_{ij} is the length of bracing member i in story j, nbm is the number of bracing members for each story and *SCLF* is the steel cost location factor. The sizes of bracing members are changed every four stories to account for changes in their induced axial forces over the height of the building.

Figure 3.A.6 shows the resistance vs. mass relationship for a tension bracing member, while Figure 3.A.7 shows the same for a compression bracing member that is 7.21m long. Figure 3.A.8 demonstrates the relationship between cross-sectional area and radius of gyration for the steel sections in Table 3.A.6 (this relationship is used to express the equation for compression resistance of bracing members solely in terms of cross-section area A).

To facilitate access to the area within the structural core, shear wall openings of three meters (3m) width are introduced on each side of the core. Furthermore, the structural shear-wall box is designed as a vertical cantilever beam column that carries, in addition to lateral loads, gravity loads corresponding to the tributary area of the columns that are replaced by the structural core.

Table 3.A.6: Steel Sections used for Bracing Members

Designation	Mass (kg/m)	CSA[1] (mm^2)	Designation	Mass (kg/m)	CSA[1] (mm^2)	Designation	Mass (kg/m)	CSA[1] (mm^2)
HSS 610-13	187	23800	HSS 324-9.5	73.9	9410	HSS 114-8	20.9	2660
HSS 610-11	164	20900	HSS 324-8	61.9	7890	HSS 114-6.4	16.9	2150
HSS 610-9.5	141	18000	HSS 324-6.4	49.7	6330	HSS 114-4.8	12.9	1640
HSS 559-13	171	21800	HSS 273-13	81.6	10400	HSS 102-8	18.4	2340
HSS 559-11	150	19100	HSS 273-11	71.9	9160	HSS 102-6.4	14.9	1900
HSS 559-9.5	129	16400	HSS 273-9.5	61.9	7890	HSS 102-4.8	11.4	1450
HSS 508-13	155	19800	HSS 273-8	52	6620	HSS 102-3.8	9.19	1170
HSS 508-11	136	17400	HSS 273-6.4	41.8	5320	HSS 89-8	15.9	2020
HSS 508-9.5	117	14900	HSS 219-13	64.6	8230	HSS 89-6.4	12.9	1650
HSS 508-8	98	12500	HSS 219-11	57.1	7270	HSS 89-4.3	9.92	1260
HSS 406-13	123	15700	HSS 219-9.5	49.3	6270	HSS 89-3.8	8	1020
HSS 406-11	108	13800	HSS 219-8	41.4	5270	HSS 73-6.4	10.4	1330
HSS 406-9.5	93.3	11900	HSS 219-6.4	33.3	4240	HSS 73-4.8	8.04	1020
HSS 406-8.0	78.1	9950	HSS 219-4.8	25.3	3220	HSS 73-3.8	6.5	828
HSS 406-6.4	62.6	7980	HSS 168-9.5	37.3	4750	HSS 73-3.2	5.48	698
HSS 356-13	107	13700	HSS 168-8	31.4	4000	HSS 60-6.4	8.45	1080
HSS 356-11	94.6	12000	HSS 168-6.4	25.4	3230	HSS 60-4.8	6.54	834
HSS 356-9.5	81.3	10400	HSS 168-4.8	19.3	2460	HSS 60-3.8	5.31	676
HSS 356-8	68.2	8680	HSS 141-9.5	31	3950	HSS 60-3.2	4.48	571
HSS 356-6.4	54.7	6970	HSS 141-8	26.1	3330	HSS 48-1.8	5.13	654
HSS 324-13	97.5	12400	HSS 141-6.4	21.1	2690	HSS 48-3.8	4.18	533
HSS 324-11	85.8	10900	HSS 141-4.8	16.1	2050	HSS 48-3.2	3.54	451

[1] *Cross Sectional Area.*

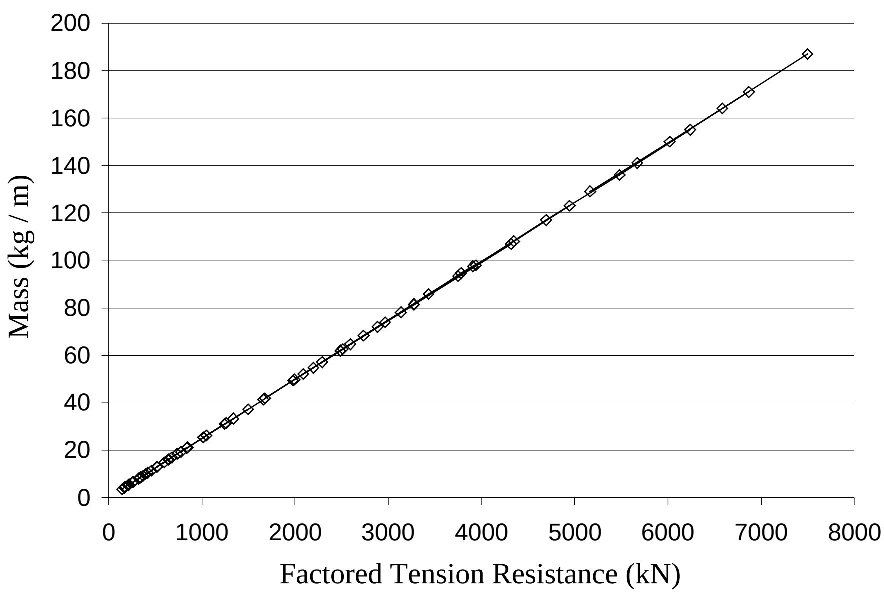

Figure 3.A.6: Factored Tension Resistance vs. Mass for Bracing Members

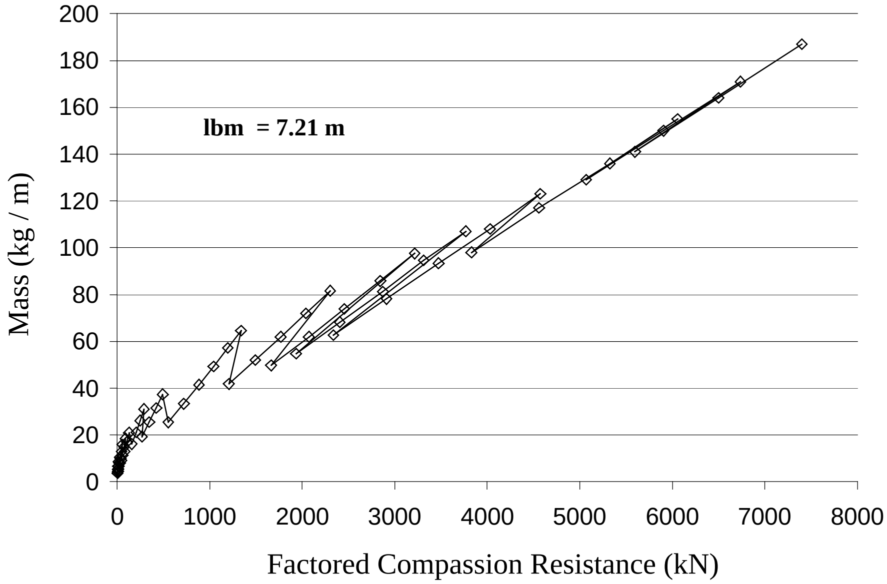

Figure 3.A.7: Factored Compression Resistance vs. Mass for Bracing Members

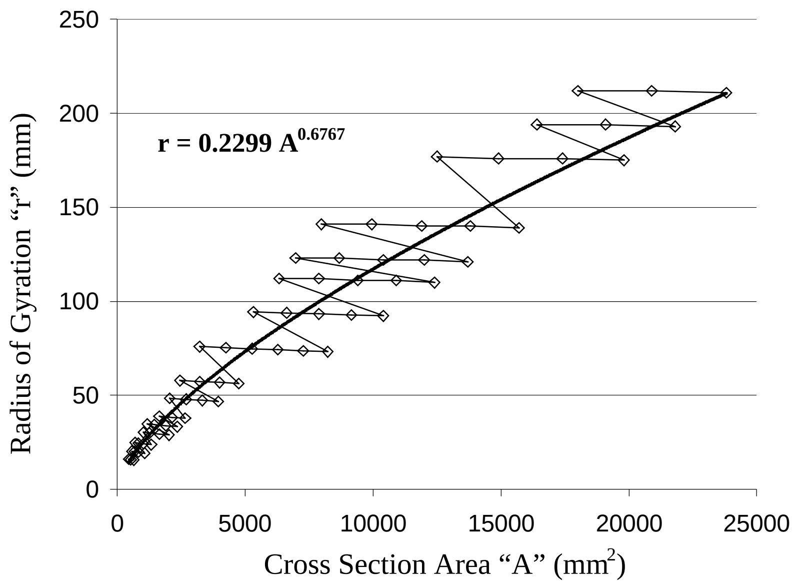

Figure 3.A.8: Cross Sectional Area vs. Radius of Gyration for Bracing Sections

To simplify the approximate analysis of the lateral load resisting system, it is assumed that the coupling beams connecting the four corners of the structural core together are infinitely rigid and that shear flow analysis can be used to estimate their shear forces and bending moments. Finally, it is assumed that the design of each shear wall prevails constant over four stories of the building. The cost of shear walls and coupling beams is found as,

$$\begin{aligned} Cost_{\text{Shear wall and coupling beams}} = \sum_{i=1}^{NF} \Big(& Rebar_{mass} \times RCLF \times Rebar_{unit\ cost} + \\ & Concrete_{volume} \times CCLF \times Concrete_{unit\ cost} + \\ & Forming_{area} \times FCLF \times Forming_{unit\ cost} \Big)_i \end{aligned} \qquad (3.A.7)$$

where *NF* is the number of floors and, as previously defined, *RCLF, CCLF and FCLF* are cost location factors (Table 2.1).

The Portal Method of approximate analysis is the basis for determining the size and, hence, the cost of structural elements in tubular systems. Only lateral loads are considered in the design of spandrel beams. The steel sections in Table 3.A.7 are used in the design of spandrel beams in steel tubular systems. Figure 3.A.9a demonstrates the mass vs. factored moment of resistance relationship for all sections in Table 3.A.7, while Figure 3.A.9b demonstrates that for only those sections in Table 3.A.7 that are the most economical to carry bending moments. In the same manner, Figure 3.A.10a represents the relationship between mass and factored shear resistance for all sections in Table 3.A.7, while Figure 3.A.10b only refers to those sections in Table 3.A.7 that are the best for resisting shear force. Each spandrel beam is designed for both shear force and bending moment, and the appropriate mass is assigned to the beam in accordance with the governing shear or bending case. In concrete tubular systems, it is assumed that the height of the beam is twice its width (for a minimum width of 250mm). Concrete spandrel beams are designed for both shear and bending and their costs are defined by their concrete volume, mass of reinforcement and area of forming. In stories where the floor system alone can overcome forces induced by combined gravity and lateral loads, no extra cost for spandrel beams is considered. The costs of spandrel beams for steel and concrete frame tube systems are found as,

$$Cost_{\text{Steel spandrel beam}} = \sum_{i=1}^{NF} (SBeaM \times SCLF \times Steel_{\text{unit cost}})_i \tag{3.A.8}$$

$$\begin{aligned} Cost_{\text{Concrete spandrel beams}} = \sum_{i=1}^{NF} (&Rebar_{mass} \times RCLF \times Rebar_{\text{unit cost}} + \\ &Concrete_{volume} \times CCLF \times Concrete_{\text{unit cost}} + \\ &Forming_{area} \times FCLF \times Forming_{\text{unit cost}})_i \end{aligned} \tag{3.A.9}$$

where: *SBeaM* is the total mass of steel spandrel beams around each floor; the mass of reinforcement bars, volume of concrete and area of forming are for the entire length of concrete spandrel beams around each floor; and *SCLF*, *RCLF*, *CCLF* and *FCLF* are the corresponding cost location factors. The design of spandrel beams is changed every four stories to account for the changes in their induced forces over the height of the building.

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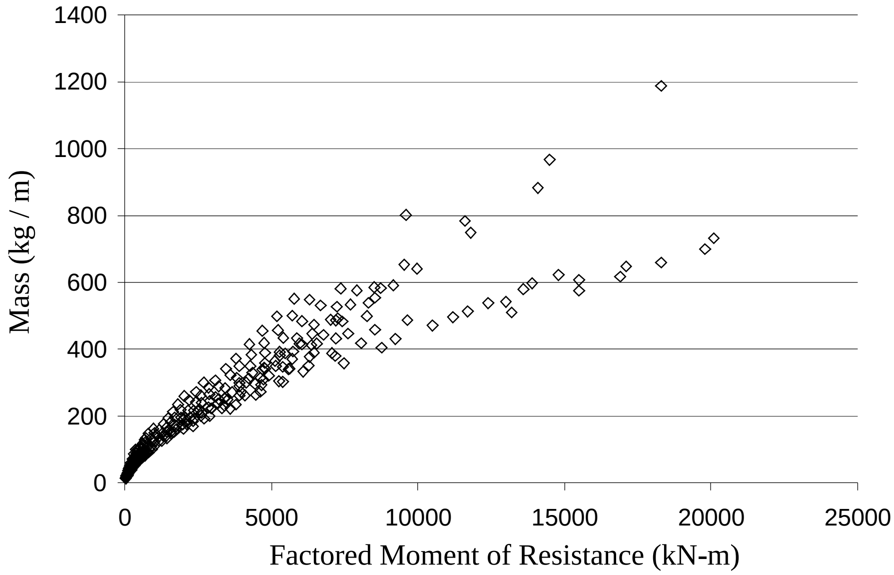
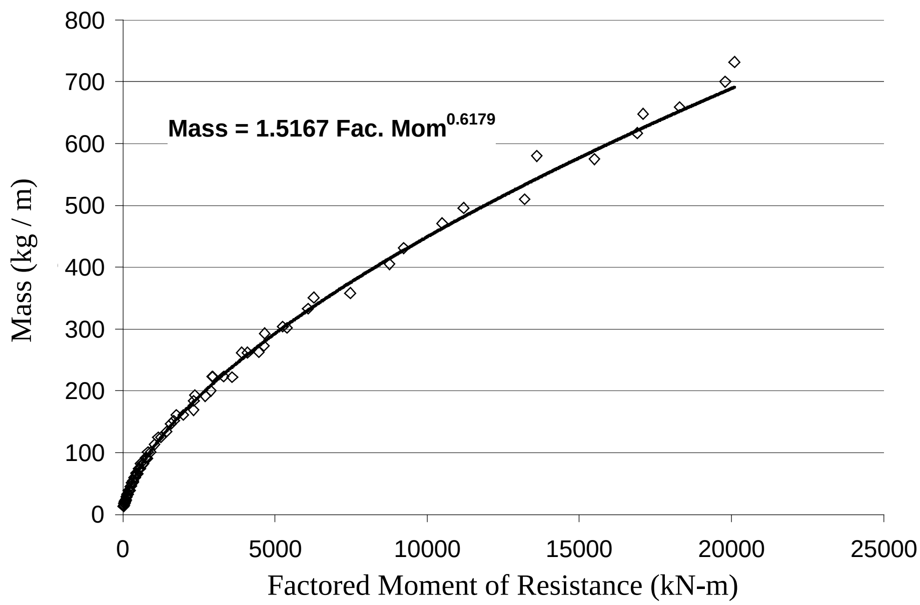
Table 3.A.7: Sections for Steel Spandrel Beams in Tubular Systems

W 920-1188	WWF 1400-471	WWF 1200-333	W 920-223	W 610-140	W 460-74	W 310-28
W 920-967	WWF 1100-458	W 840-329	WWF 800-223	W 530-138	W 410-74	W 250-28
W 1000-883	W 690-457	W 690-323	W 1000-222	W 760-134	W 310-74	W 200-27
W 690-802	W 610-455	W 1000-321	W 760-220	W 360-134	W 250-73	W 250-25
W 920-784	WWF 1000-447	W 1000-314	W 530-219	W 410-132	W 530-72	W 310-24
W 1000-749	W 920-446	W 760-314	W 690-217	W 310-129	W 360-72	W 250-24
WWF 2000-732	W 1000-443	W 920-313	W 610-217	W 460-128	W 200-71	W 150-24
WWF 1800-700	W 760-434	WWF 900-309	WWF 700-214	W 690-125	W 460-68	W 250-22
WWF 1800-659	W 840-433	W 610-307	W 460-213	W 610-125	W 460-67	W 200-22
W 920-653	W 1100-432	WWF 1100-304	W 840-210	W 530-123	W 410-67	W 150-22
WWF 2000-648	WWF 1600-431	WWF 1200-302	W 920-201	W 360-122	W 310-67	W 310-21
W 1000-641	W 690-419	WWF 800-300	WWF 1000-200	W 310-118	W 250-67	W 200-21
WWF 1600-626	WWF 1200-418	W 530-300	W 760-196	W 410-114	W 530-66	W 200-19
WWF 1800-617	WWF 900-417	W 840-299	WWF 700-196	W 610-113	W 360-64	W 250-18
WWF 2000-607	W 920-417	W 1000-296	W 530-196	W 460-113	W 460-61	W 150-18
WWF 1400-597	W 610-415	WWF 1000-293	W 610-195	W 360-110	W 460-60	W 200-15
W 1000-591	W 1000-414	W 920-289	W 840-193	W 530-109	W 410-60	W 150-14
W 920-585	W 1000-412	W 690-289	W 460-193	W 310-107	W 310-60	W 150-13
W 1000-583	WWF 1400-405	W 610-285	WWF 900-192	W 460-106	W 200-59	
W 760-582	W 1000-393	W 760-284	W 690-192	W 610-101	W 250-58	
WWF 1600-580	W 840-392	WWF 1100-273	W 760-185	W 530-101	W 360-57	
W 840-576	W 1100-390	W 1000-272	WWF 800-184	W 360-101	W 410-54	
WWF 1800-575	W 760-389	W 530-272	W 530-182	W 250-101	W 460-52	
W 1000-554	WWF 1100-388	W 920-271	W 460-177	W 410-100	W 310-52	
W 610-551	W 920-387	W 690-265	W 840-176	W 200-100	W 200-52	
W 690-548	W 690-384	WWF 1200-263	WWF 700-175	W 460-97	W 360-51	
WWF 2000-542	W 920-381	WWF 1000-262	W 610-174	W 310-97	W 250-49	
W 1000-539	WWF 1200-380	WWF 900-262	W 760-173	W 610-92	W 410-46	
WWF 1600-538	WWF 1000-377	W 610-262	W 690-170	W 530-92	W 200-46	
W 920-534	W 610-372	W 460-260	WWF 900-169	W 610-91	W 360-45	
W 760-531	W 1000-371	W 760-257	W 530-165	W 360-91	W 310-45	
W 840-527	W 920-365	W 920-253	W 360-162	W 460-89	W 250-45	
WWF 1400-513	W 840-359	WWF 800-253	WWF 800-161	W 250-89	W 200-42	
WWF 1800-510	WWF 1400-358	W 840-251	W 760-161	W 310-86	W 410-39	
W 690-500	WWF 1100-351	W 1000-249	W 460-158	W 200-86	W 360-39	
W 1100-499	W 1000-350	W 530-248	W 610-155	W 530-85	W 310-39	
W 610-498	W 760-350	WWF 700-245	W 610-153	W 410-85	W 250-39	
WWF 1600-496	W 690-350	W 610-241	WWF 700-152	W 610-84	W 150-37	
W 1000-493	WWF 900-347	W 690-240	W 690-152	W 610-82	W 200-36	
W 920-488	W 920-345	W 920-238	W 530-150	W 530-82	W 360-33	
WWF 1200-487	W 1100-342	W 460-235	W 410-149	W 460-82	W 310-33	
W 1000-486	W 920-342	WWF 1100-234	W 760-147	W 250-80	W 250-33	
W 760-484	W 610-341	WWF 900-231	W 360-147	W 360-79	W 310-31	
W 1000-483	WWF 1000-340	W 840-226	W 460-144	W 310-79	W 200-31	
W 840-473	WWF 800-339	WWF 1000-223	W 690-140	W 530-74	W 150-30	

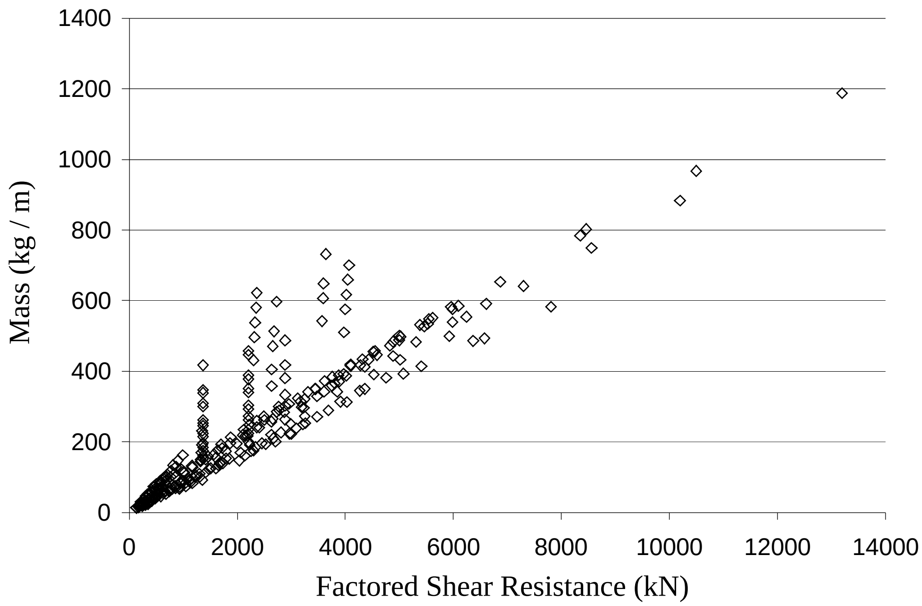


(a) All sections in Table 3.A.7

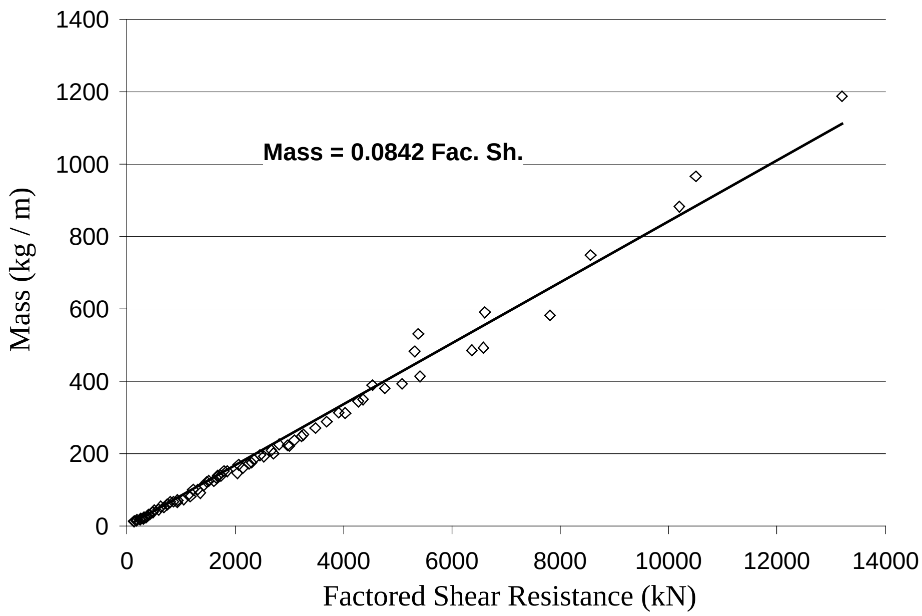


(b) Economical moment sections in Table 3.A.7

Figure 3.A.9: Mass vs. Factored Moment Resistance in Steel Spandrel Beams



(a) All sections in Table 3.A.7



(b) Economical shear sections in Table 3.A.7

Figure 3.A.10: Mass vs. Factored Shear Resistance in Steel Spandrel Beams

3.A.5 Cost of Stairs

The width and number of risers for stairs are functions of the story height and the floor plan dimensions. Since the cost of steel and concrete stair cases are almost equal (Mean's manual 1999), and since steel stair cases have the advantage of being easily constructible for both steel and concrete structures, this study only considers steel stair cases. Figure 3.A.11 represents the relation between the cost of a 1.2 meter wide steel stair case and the number of risers. The cost of the stair cases for all *NF* floors of a building is found as (Mean's manual 1999),

$$Cost_{\,Stair\ case} = NSC \times \frac{WSC}{1.2} \times NF \times SCLF \times (181.88 \times NRSC + 1320) \qquad (3.A.10)$$

where *NSC* and *WSC* are the number and width of stair cases, respectively, *NRSC* is the number of risers between floors, and *SCLF* is the steel cost location factor.

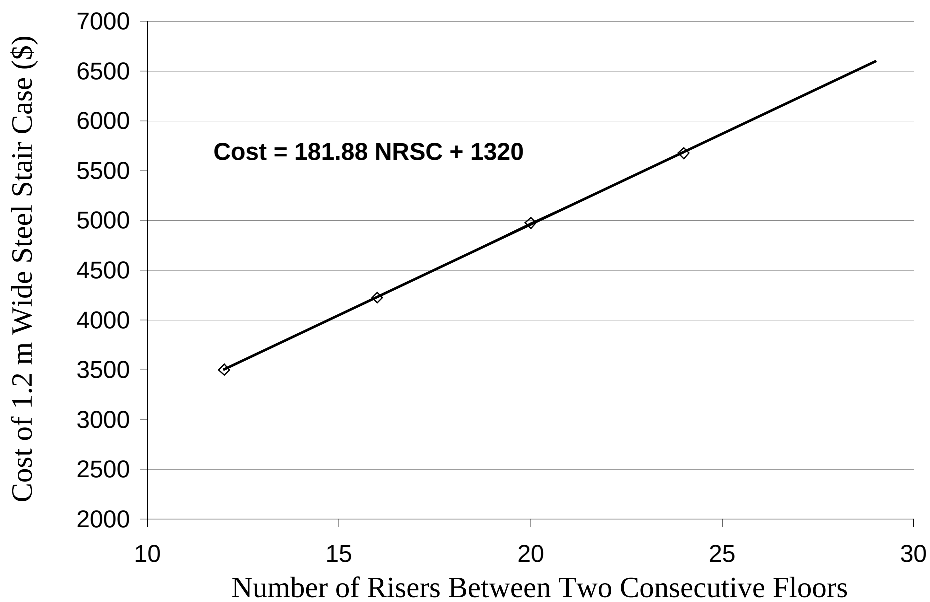


Figure 3.A.11: Cost of 1.2 m Wide Stair Case vs. Number of Risers

3.A.6 Cost of Façade and Roofing

The cost of the façade comprises the cost of windows and cladding, assuming that mechanical floors do not have any windows. The roofing cost comprises the cost of material and workmanship involved in insulating the roof of the building. Table 3.A.8 presents unit costs and some properties of window, cladding and roofing elements. Corresponding costs are represented by the products of the areas of windows, cladding and floor plan times the unit costs of windows, cladding and roofing, respectively. These areas and costs are found as,

$$Area_{\,Window} = WIR \times (D_a + D_b) \times 2 \times RNF \times (h_{cle}\text{-}1) \tag{3.A.11a}$$

$$Area_{\,Cladding} = (D_a + D_b) \times 2 \times H - Area_{\,Window} \tag{3.A.11b}$$

$$Area_{\,Roof} = D_a \times D_b \tag{3.A.11c}$$

$$Cost_{\,Window} = Area_{\,Window} \times WCLF \times Window_{\,Unit\ cost} \tag{3.A.12a}$$

$$Cost_{\,Cladding} = Area_{\,Cladding} \times C_LCLF \times Cladding_{\,Unit\ cost} \tag{3.A.12b}$$

$$Cost_{\,Roofing} = Area_{\,Roof} \times R_OCLF \times Roofing_{\,Unit\ cost} \tag{3.A.12c}$$

where *WIR* and *RNF* are window ratio and rentable number of floors, respectively, *WCLF*, C_LCLF and R_OCLF are window, cladding and roofing cost location factors, respectively, and h_{cle} is the floor-to-ceiling clearance distance.

Table 3.A.8: Unit Costs and Properties of Building Envelope Components

Cladding and Window types	Cost $/m^2	Thermal Transmittance W/m^2 K	Shading Coefficient (Unit less)
Pre-cast concrete	215	0.44	-
Metal siding panel	90	0.71	-
Stucco wall	105	0.69	-
Glazing panel	235	0.75	-
Standard glass	285	6.3	0.95
Insulated glass	310	3.5	0.82
Standard HA	305	6.3	0.71
Insulated HA	330	3.5	0.56
Roofing	63	0.7	-

3.A.7 Cost of Finishing and Partitioning

Tenants in office buildings usually pay for their own interior office partitions and finishes, while the owner/developer pays for the exterior shell of the building and the main interior walls, including toilet partitions and elevator walls, floor and ceiling finishes, and finishes required for interior surfaces of exterior walls (The Toronto Real Estate Board 1999). As such, the cost function adopted by this study for finishing and partitioning pertains only to that paid for by the owner/developer (i.e., rental area finishing costs are not considered). The finishing cost, then, is the product of the floor and wall surface areas times finishing unit costs, with account for the prevailing cost location factor, i.e.,

$$Cost_{\,Finishing} = (NF \times D_a \times D_b \times Finishing_{\,unit\ cost} + NF \times ISA \times Wall\ Finishing_{\,unit\ cost}) \times F_I CLF \tag{3.A.13}$$

where ISA is the interior surface area of exterior walls and $F_I CLF$ is the cost location factor for finishing.

3.A.8 Cost of HVAC System

The cost of the HVAC system for a building includes a cost that is directly based on the size of the floor area (i.e. costs for plumbing, ducts, fan units, and water sprinkler), i.e.,

$$Cost_{\,plumbing,\ ducts,\ fan\ units,\ water\ sprinkler} = NF \times D_a \times D_b \times MCLF \times Mechanical_{\,unit\ cost} \tag{3.A.14}$$

where $MCLF$ is the mechanical cost location factor. Other HVAC costs for boilers, chillers and related components involve more detailed calculation, as described in the following.

To establish an accurate estimate of the cost of the HVAC system for a building it is necessary to calculate its heating and cooling loads, which are defined by the amount of energy per unit time that must be given to or removed from the building in order for its environment to be acceptable to the occupants. The HVAC heating and cooling loads are functions of the building dimensions, exterior walls, window material and area, the external environmental conditions, the desired inside temperature and humidity, and the geographical location and orientation of the building. In lieu of an exact analysis to establish the heating and cooling loads (which involves considering every day of the year), this study only focuses on twelve representative days corresponding to the twelve months of a year, which results in an acceptable estimation of maximum cooling and heating loads.

The first step taken to calculate HVAC heating and cooling loads involves finding the outside temperatures and the energy given to the building from sun radiation at any hour of the twelve sample days. To this end, this study proposes the use of sinusoidal functions in conjunction with American Society of Heating, Refrigerating and Air-Conditioning Engineers guidelines (ASHRAE, 1989) to estimate the maximum and minimum temperatures $TMAX_m$ and $TMIN_m$ for any given sample day, and the temperature for any given hour of the day, knowing only the annual maximum and minimum temperatures and their daily ranges. The sinusoidal functions used to estimate $TMAX_m$ and $TMIN_m$ for any of the twelve sample days are,

$$TMAX_m = \frac{AHDT_{max} + ACDT_{max}}{2} + \left|\frac{AHDT_{max} - ACDT_{max}}{2}\right| \times COS\left(\pi \frac{m-7}{6}\right) \tag{3.A.15a}$$

$$TMIN_m = \frac{AHDT_{min} + ACDT_{min}}{2} + \left|\frac{AHDT_{min} - ACDT_{min}}{2}\right| \times COS\left(\pi \frac{m-7}{6}\right) \tag{3.A.15b}$$

where $AHDT_{max}$ and $AHDT_{min}$ are the average maximum and minimum temperatures for a hot day in July, and $ACDT_{max}$ and $ACDT_{min}$ are the average maximum and minimum temperatures for a cold day in January, and subscript m = 1,….,12 where 1= January and 12= December.

Since the earth moves around the sun in an almost circular motion, Eqs. (3.A.15) estimate the changes in temperature over the year very well. Figure 3.A.12 illustrates the close proximity between the temperatures found from Eqs. (3.A.15) and the actual change in outside temperature for New York City; $TMAX_m$ and $TMIN_m$ are shown by continuous lines superimposed on the actual air temperatures in broken lines (Olgyay 1992).

The sinusoidal function used to estimate hourly temperatures for any given day of the twelve sample days is,

$$T_{mh} = \frac{TMAX_m + TMIN_m}{2} + \left|\frac{TMAX_m - TMIN_m}{2}\right| \times COS\left(\pi \frac{h-15}{12}\right) \tag{3.A.16}$$

where T_{mh} is the outside temperature for any $h = 1^{st},\ldots,24^{th}$ hour of the day in any given month m. Eq. (3.A.16) ensures that the maximum and minimum daily temperatures occur at 3pm and 3am, respectively, which is very close to reality. The ASHRAE (1989) hand book of HVAC fundamentals suggests the use of a set of constants in order to estimate the change of air temperature within a day. Figure 3.A.13 shows that the hourly changes in temperature found using the ASHRAE constants compare well with those found using Eq. (3.A.16).

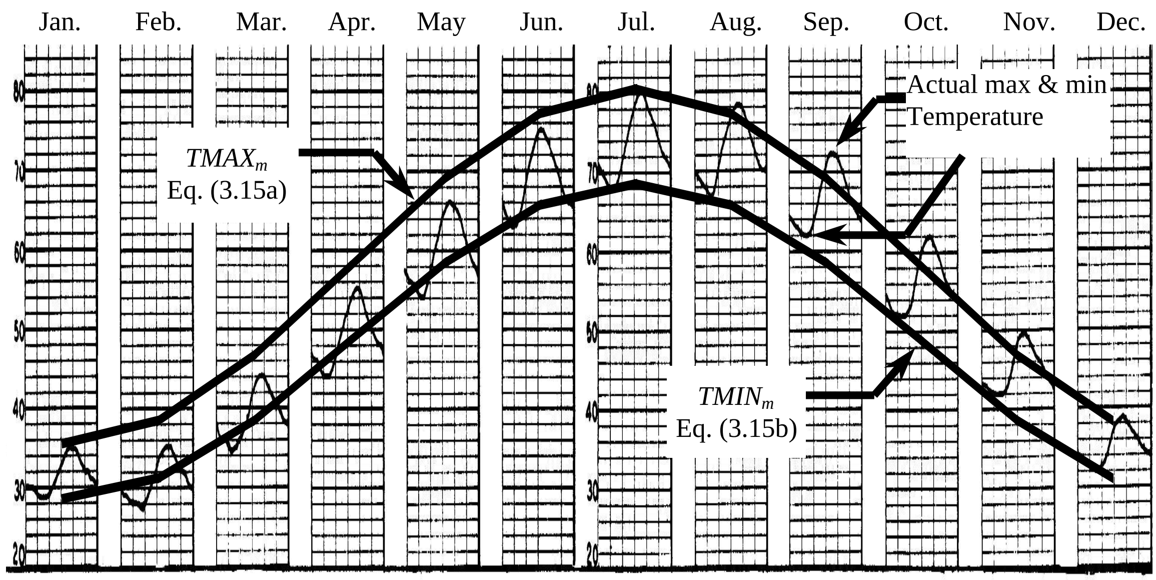


Figure 3.A.12: Comparison Between Sinusoidal Function and Actual Climate Change

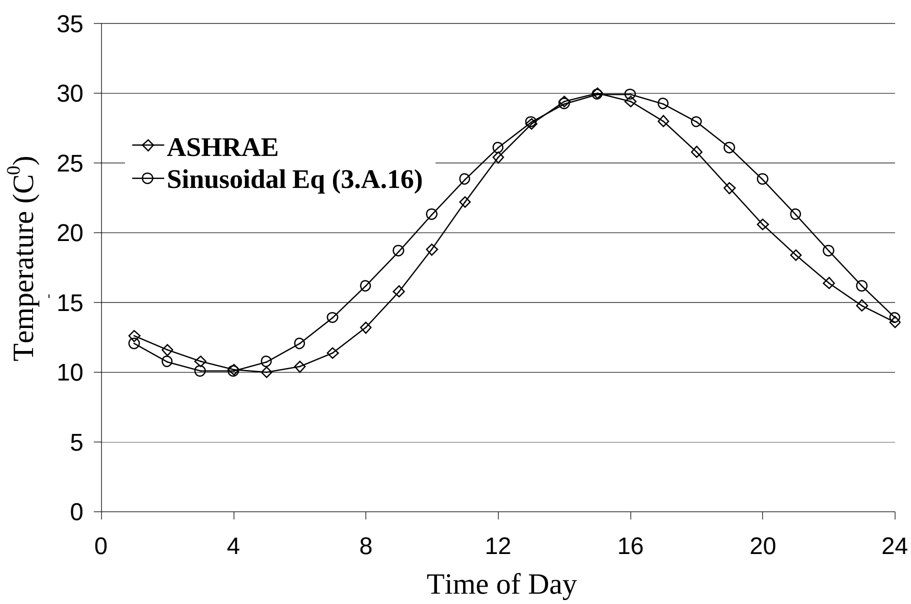


Figure 3.A.13: Change of Temperature During 24 Hours of a Day

Temperatures found using Eqs. (3.A.15) and (3.A.16) are directly used to calculate heat gain or loss through ventilation and conduction of windows. The additional gains and losses of energy due to solar radiation are estimated by increasing or decreasing the temperature on the surface of the cladding and roof and calculating the solar heat gain through the windows (ASHREA 1989). Solar heat gain or loss caused by radiation of the sun and radiation of the building at night to the clear sky are functions of the geographical location and orientation of the building (ASHREA 1989). In lieu of a rigorous method to calculate the heating and cooling loads for an office building, this study uses an approximate method that divides the building into four zones (Figure 3.A.14) and then conducts an analysis of each zone to find out if it needs to be heated or cooled at any given time over the day. After establishing heating and cooling loads in this way for all 24 hrs of the twelve sample days, the maximum heating and cooling loads for the building are then found by combining the loads of the four zones.

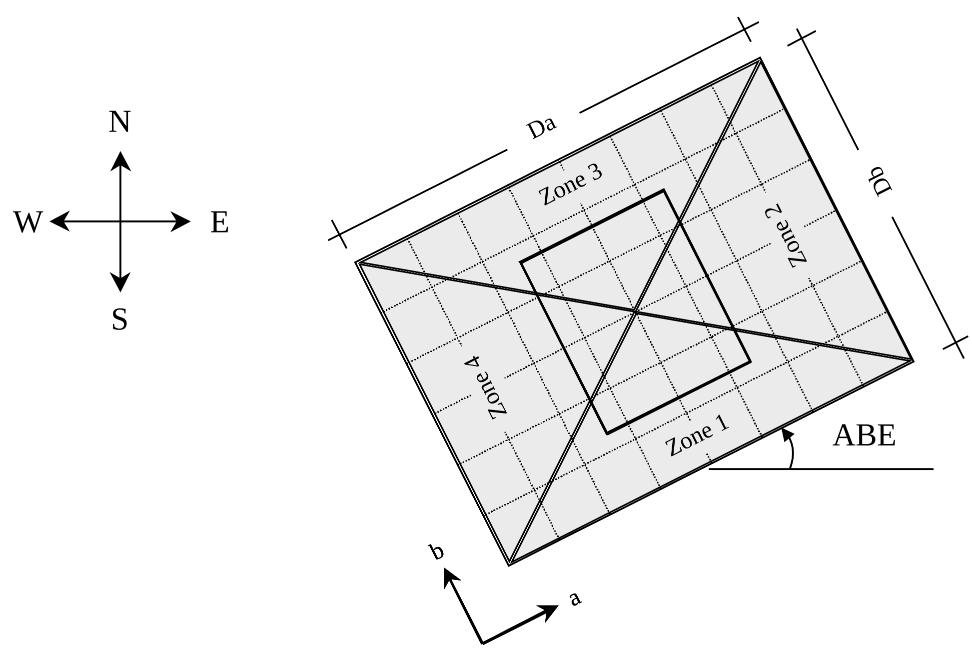


Figure 3.A.14: Air Conditioning Zoning for a Typical Building

The loads imposed on the building by the occupants, lighting system and equipment should also be considered in addition to the heating energy injected into the building by ventilation, conduction of the building envelope and solar heat gain through the windows and walls. Albeit, to conservatively establish the heating load on a cold day, this additional heat is typically neglected to arrive at the worse-case scenario.

This study employs the ASHRAE (1989) guidelines to establish the annual heating and cooling loads for a typical building having the following properties:

D_a = 50 m	*HDTR* = 20 ^{0}C
D_b = 40 m	AOT_{min} = -15 ^{0}C
H = 124 m	*HDTR* = 10 ^{0}C
RNF =30	*DIT* = 20 ^{0}C
WIT= Insulated HA	*IRH* = 50%
WIR = 50%	*LA* = 40 ^{0} N
WAT= precast concrete	*ABE* = 0 ^{0}
AOT_{max} = 30 ^{0}C	

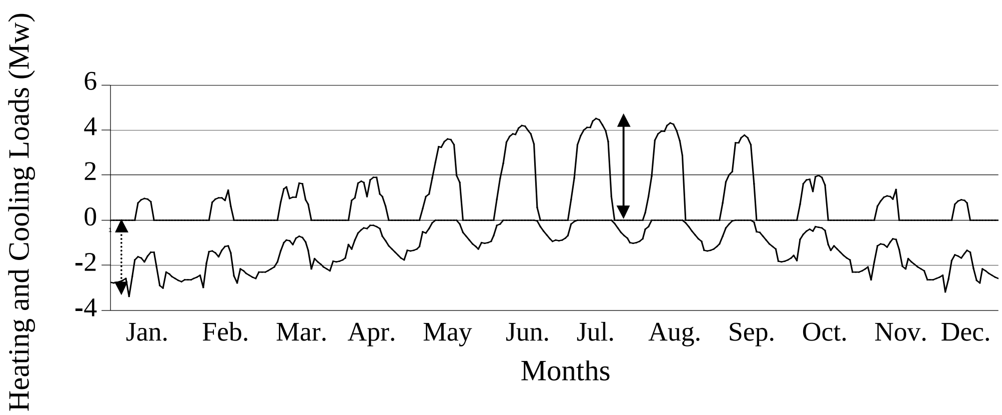


Figure 3.A.15: Heating & Cooling Loads vs. Time for a Typical Building

The annual heating and cooling loads are illustrated in Figure 3.A.15, where the vertical dashed and continuous double arrows indicate the magnitudes of the maximum heating and cooling loads, respectively. Having the annual heating and cooling loads for a building, such as in Figure 3.A.15, the costs of boilers and chiller/cooling towers are estimated as,

$$Cost_{Boilers} = Annual\ Heating_{Load} \times MCLF \times Boilers_{unit\ cost} \tag{3.17a}$$

$$Cost_{Chillers\ \&\ cooling\ towers} = Annual\ Cooling_{Load} \times MCLF \times Chillers\ \&\ Cooling\ tower_{unit\ cost} \tag{3.17b}$$

where *MCLF* is the mechanical cost location factor.

3.A.9 Cost of Elevators

The number of elevators is a function of the total building floor area rather than the number of stories or floor plan area. This is because the number of elevators is kept constant, while their speed is increased, as the building height increases. This results in higher cost for elevators in taller buildings, mainly because of higher costs for motors and gears required to accommodate faster speeds over longer distances. As such, the cost of each elevator is a function of the number of stories and the type of elevator. In this study, only one type and size of elevator is considered; the US national average cost of one such elevator vs. the number of stories is shown in Figure 3.A.16. The approximate calculation of the cost of elevators for a building with *NF* floors is given by (Mean's manual 1999),

$$Cost_{Elevators} = NE \times E_L CLF \times (8962.5 \times NF + 119625) \tag{3.A.18}$$

where *NE* is the number of elevators and E_LCLF is the elevator cost location factor.

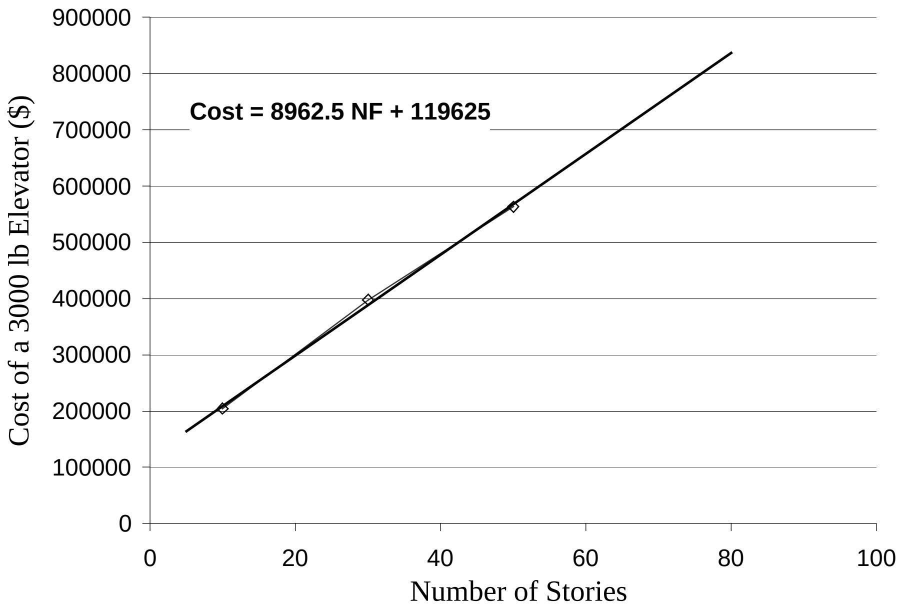


Figure 3.A.16: Cost of a 3000 lb Elevator vs. Number of Stories

3.A.10 Cost of Lighting System

The cost of the lighting system, including electrical outlets, is calculated as the product of the floor area times the electrical system unit cost with account for the prevailing cost location factor, i.e.,

$$Cost_{Lighting} = NF \times D_a \times D_b \times ECLF \times Electrical_{unit\ cost} \qquad (3.A.19)$$

where *ECLF* is the cost location factor for the electrical system.

Appendix 3.B - Annual Operating Cost (Eq. 3.3)

3.B.1 Annual Cost of Energy

The first step to approximate the annual cost of energy is to estimate the energy consumed by the HVAC, lighting, elevator and equipment systems. To establish the amount of energy consumed by the HVAC system, it is necessary to find the energy needed to heat up or cool down the building at any given time over the year. The sum of these heating and cooling energies represent the energy that is input to and removed from the building in one year. It is recommended to include all heat gain from the sun and internal sources to arrive at an accurate estimation of annual heating energy (ASHRAE 1989). Since it is not realistic to assume a clear sky at all times, which causes over-estimation of heat gains and losses, this study employs a clear sky factor found from local environmental information to reduce both the temperature increase of cladding and the incoming energy through windows due to solar radiation. Figure 3.B.1 demonstrates the added heating and removed cooling energies for a typical building example at any hour of the twelve sample days. The area above the solid line represents the heating energy, while the area beneath the broken line signifies the cooling energy. Heating and cooling energies found from Figure 3.B.1 are multiplied by the average number of days in a month to arrive at the energy consumed for the entire year. The energy operating cost for a HVAC system is found as,

$$\textit{Operating Cost}_{\textit{HVAC energy}} = \textit{Annual}_{\textit{heating energy}} \times \textit{Gas energy}_{\textit{unit cost}} + \textit{Annual}_{\textit{cooling energy}} \times \textit{Electrical energy}_{\textit{unit cost}} \qquad (3.B.1)$$

where the heating and cooling energy unit costs are defined by the unit costs of gas and electricity, respectively.

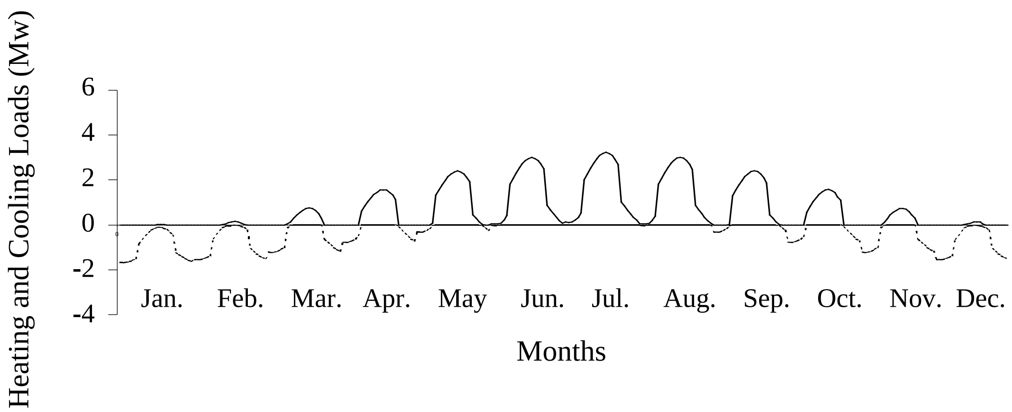


Figure 3.B.1: Heating & Cooling Energies vs. Time for a Typical Building

To arrive at the total annual cost of energy, the cost of energy consumed by lighting and elevator systems and office equipment must be added to the HVAC energy cost. To this end, Table 3.B.1 represents the energy load for these systems during working and non-working hours. Hence, the operating energy cost for the lighting, and elevator equipment systems is found as,

$$\textit{Operating Cost}_{\textit{Lighting, elevators and equipment energy}} = \textit{Annual Energy}_{\textit{Lighting, elevators and equipment}} \times \textit{Electrical energy}_{\textit{unit cost}} \qquad (3.B.2)$$

where the annual energy for lighting, elevators and equipment is the sum of the energy they individually consume in working and non-working hours over a year.

Table 3.B.1: Energy Loads for Lighting, Elevator and Equipment Systems

	Lighting		Elevators and Equipment	
	Working hrs.	Non-working hrs.	Working hrs.	Non-working hrs.
Energy Load (w/m^2)	20	10	15	7.5

3.B.2 Annual Maintenance Cost.

The annual cost of building maintenance work is a function of the upkeep costs for the mechanical and electrical systems, facade and roofing, and the building's finishing. No annual maintenance cost is associated with structural components since they are protected by the building shell and theoretically designed to last indefinitely (CSA, Canadian Standards Association, 1995). This study finds the annual maintenance cost for a building as,

$$\textit{Operating Cost}_{\textit{Maintenance}} = \textit{Partial Building Capital Cost} \times \textit{Maintenance Factor} \quad (3.B.3)$$

where the partial building capital cost refers only to those systems or components of the building that are in need of maintenance, and the maintenance factor is a fixed percentage of that capital cost (e.g., see Table 4.1).

3.B.3 Annual Property Tax

The operating cost associated with annual property tax is usually a function of the value of the building and the municipality tax rate (The Toronto Real Estate Board 1999), i.e.,

$$\textit{Operating Cost}_{\textit{Tax}} = \textit{Building Value} \times \textit{Tax Rate} \quad (3.B.4)$$

where tax rates are defined by municipal authorities and value of the building is a function of the locality and leaseable area of the building.

Appendix 3.C - Genetic Algorithms

Genetic algorithms (GA's) are search algorithms based on the principles of natural selection (survival of the fittest) and genetics. They involve structured yet randomized exchanges of information among candidates of a population of solutions that progressively improve the average fitness of the population until convergence occurs to a 'best' solution. While the operations of genetic algorithms are randomized they are by no means simple random walks. They efficiently exploit historical information to speculate on new search directions for which improved fitness is expected to occur for candidate solutions. Since the development of GA's by Holland and his colleagues (1975), they have been applied to commerce, engineering, mathematics, medicine, and pattern recognition with promising results (Goldberg 1989). A number of studies have efficiently applied GA's to optimum structural design (e.g., Adeli et al., 1993; Grierson and Pak, 1993; Jenkins, 1994; etc), conceptual design (Goldberg, 1991; Mathews et al.,1994; Grierson, 1997), and multi-criteria optimization (Gero et al.,1995; Kundu, 1996; Park and Grierson, 1997).

Genetic algorithms work with a coding (e.g., binary) of the variables, not the actual variables themselves. This makes them computationally well suited for treating discrete variables. However, they can treat continuous variables when the required precision is specified. Moreover, as GA's work simultaneously with a population of solutions, they are able to operate in multi-modal solution spaces without the need for gradient information. In essence, they use directed random choice as a tool to guide the search toward regions of the space having more desirable values for the prevailing objective function(s) for the problem.

For binary coding, each solution in the population of solutions is represented by a bit string, the length of which depends on the cardinal number of the bit, the number of variables, and the number of discrete values that each variable can assume. For example, consider a conceptual design problem for a high-rise office building having primary design variables whose base-10 and binary (base-2) values are as shown in Tables 3.1, and 3.2, respectively. From Table 3.1, variable ST has 10 possible choices, variables S_a, S_b and WIR each have 16 choices, variables NS_a, NS_b and CDF each have 8 choices, variables CFT, SFT, TS_a, TS_b, WIT, and WAT each have 4 choices values and, finally, variables BT and $DCDD$ each have two possible choices. Therefore, the variables ST, S_a, S_b, and WIR can each be represented by a 4-bit binary code, the variables NS_a, NS_b and CDF by a 3-bit binary code, the variables CFT, SFT, TS_a, TS_b, WIT and WAT by a 2-bit binary code and, finally, the variables BT and $DCDD$ can each be represented by a 1-bit binary code. Hence, any one design is represented by a 4x4+3x3+6x2+2x1= 39-bit string. Note that only some parts of this binary code is applicable for any given design in that some information is not applicable for certain structure types (as indicated by NA below). For example, the binary code for a particular conceptual design of an office building may be:

ST	BT	CFT	SFT	S_a	S_b	NS_a	NS_b	NTS_a	NTS_b	$DCDD$	CDF	WIT	WIR	WAT
0011	0	10 NA	11	1010	0111	101	011	01 NA	10 NA	1	100	10	1001	11

which, from Tables 3.1 and 3.2, decodes as a steel rigid frame with a composite steel beam and deck and concrete slab floor system having 8 and 6 spans of 9.5 m and 8.0 m length in the *a* and *b* directions, respectively, a core having a *b* dimension that is 0.564 times the *b* dimension of the building foot print, standard heat absorbing windows, a 70% window ratio and a glazed panel cladding system.

The GA commences by randomly selecting an initial population of arbitrary solutions (e.g., a population of 39-bit strings). The relative fitness F of each solution is assessed through its performance fitness function,

$$F = F_{max} - \Phi(x) \tag{3.C.1}$$

where F_{max} is an arbitrarily large positive number that ensures the fitness is always positive, $\Phi(x)$ is an objective function with built-in penalties reflecting any constraint violations for a solution, and $x = [x_1\ x_2\ \ldots.x_n]$ represents the variable vector for the problem. Having the fitness of all designs, genetic operators are then applied to create a new population of solutions having better average fitness. The three most commonly used operators are: selection (parents); crossover (simulated mating); and mutation (random diversity).

The reproduction cycle consists of the selection and crossover operations and is the heart of the genetic algorithm that creates new and, probably, fitter solutions. Selection is the process of choosing parents from the current population for subsequent mating to create offspring for the next generation. There are several selection techniques, such as pure-random, fit-fit, fit-weak and roulette wheel methods (Chambers, 1995). In the pure random method, the parents are selected from the population at random. Fit-fit selection pairs an individual with the next fittest individual in the population by simply searching through the list of individuals. In fit-weak selection, the fittest individual is paired with the least fit, the next fittest is paired with the next least fit, and so on. The weighted roulette wheel method, which is a traditional GA selection technique, operates such that each solution occupies a portion of the weighted roulette wheel in proportion to its relative fitness. A random number is then generated and used to select a parent solution from the roulette wheel. Those solutions of high proportional fitness have a high probability of being selected as parent solutions, while those of medium and low proportional fitness have average and lower selection probability, respectively. That is, individuals of high fitness may be selected (reproduced) a number of times, those of medium fitness may be reproduced singly, and those of low fitness may not be reproduced at all in the selection process.

After the selection procedure is complete, the crossover operator is applied to create a random interchange of information between randomly paired parents. This operator carries out a structured data exchange that recombines the parent solutions according to a specified probability, using either one-site or multi-site crossover. For example, two-site crossover involves randomly selecting two splicing sites for a pair of parent solution strings, and then exchanging the information located between the two sites between the two parents. The two new strings so formed are called “children” solutions and become members of the next population. For example, for the conceptual design of the previously described high-rise building example, if a pair of parent designs and the splice (exchange) sites are as follows:

	ST		*BT*	*CFT*	*SFT*	S_a	S_b	NS_a	NS_b	NTS_a	NTS_b	*DCDD*	*CDF*		*WIT*	*WIR*	*WAT*
Parent A:	***00***	***11***	***0***	***10***	***11***	***1010***	***0111***	***101***	***011***	***01***	***10***	***1***	***10***	***0***	***10***	***1001***	***11***
Parent B:	01	00	1	11	00	1100	0011	001	110	11	00	0	00	1	01	1010	00
	Exchange Site												Exchange Site				

Then, after crossover the two child designs are:

	ST		*BT*	*CFT*	*SFT*	S_a	S_b	NS_a	NS_b	NTS_a	NTS_b	*DCDD*	*CDF*		*WIT*	*WIR*	*WAT*
Child A:	***00***	00	1	11	00	1100	0011	001	110	11	00	0	00	***0***	***10***	***1001***	***11***
Child B:	01	***11***	***0***	***10***	***11***	***1010***	***0111***	***101***	***011***	***01***	***10***	***1***	***10***	1	01	1010	00
	Exchange Site												Exchange Site				

That is, after exchanging genes, from Tables 3.1 and 3.2, Parent A (*ST* = steel rigid frame, *SFT* = composite beam, deck and slab, S_a = 9.5m, S_b = 8.0m, NS_a = 8, NS_b = 6, $C_b = 0.564 \times S_b \times NS_b$, *WIT* = standard heat absorbing glass, *WIR* = 70% and *WAT* = glazed panel) and Parent B (*ST* = steel frame and bracing, *BT* = K&X, *SFT* = steel joist & beam, deck & slab, S_a = 10.5 m, S_b = 6.0 m, NS_a = 4, NS_b = 9, Ca = $0.329 \times S_a \times NS_a$, *WIT* = insulated glass, *WIR* = 75% and *WAT* = precast concrete) are replaced by Child A (*ST* = concrete rigid frame, *CFT* = waffle slab, S_a = 10.5m, S_b = 6.0m, NS_a = 4, NS_b = 9, $C_a = 0.25 \times S_a \times NS_a$, *WIT* = standard heat absorbing glass, *WIR* = 70% and *WAT* = glazed panel) and Child B (*ST* = steel rigid frame and shear wall, *SFT* = composite beam and deck and slab , S_a = 9.5m, S_b = 8.0m, NS_a = 8, NS_b = 6, $C_b = 0.643 \times S_b \times NS_b$, *WIT* = insulated glass, *WIR*= 75% and *WAT* = precast concrete). Note that the values of the two design variables *ST* and *CDF* are changed, the values of the three design variables *WIT*, *WIR*, and *WAT* remain constant, and that the values of the rest of the variables are simply exchanged.

Even though the selection and crossover operators effectively search the solution space, they may occasionally miss some useful genetic features. To prevent such a loss and to avoid premature convergence to a local optimum, the mutation operator is applied to each bit position of each child solution string according to a preset probability of occurrence. In the case of binary coded genes, mutation is performed by flipping the value of a gene from 0 to 1 or vice versa. Typically, the mutation probability is set quite low.

After application of the selection, crossover and mutation operators to create the next generation of new solutions, the possible convergence of the GA to an optimum solution is checked. Three convergence criteria that are often adopted are described in the following. The first criterion checks to see if there is no improvement in the maximum solution fitness for the population for a specified number of consecutive generations, at which point the GA is terminated. A second criterion terminates the search if the same number of solutions have the same maximum fitness for the population for a specified number of consecutive generations. A third criterion is sensitive to the computational time required to generate the optimal solution, and causes the GA to stop running after a pre-assigned number of generations. As a GA does not embody any formal mechanism that guarantees finding the global optimum, it is generally run several to many times for a number of different randomly generated initial populations, with the expectation that most if not all runs will converge to almost the same optimum solution.

Appendix 3.D - Pareto Optimization

It is generally considered that multi-criteria optimization originated towards the end of the nineteen century when Pareto (1848-1923) presented a qualitative definition of non-preferential optimality for multiple competing criteria (Pareto, 1896). The basic concepts of multi-criteria Pareto optimization are briefly explained in the following.

The multi-criteria optimization problem may be stated as:

Minimize: $f(x) = [f_1(x), f_2(x), \ldots, f_Q(x)]^T$ (3.D.1)

Subject to : $g(x) \leq 0, h(x)=0$ (3.D.2)

where $x = [x_1\ x_2\ \ldots.\ x_n]^T$ is the vector of n variables for the problem, $f(x)$ is the vector of $i=1,2, \ ,Q$ objective functions $f_i(x)$ that are each to be minimized, and the functions $g(x) \leq 0$ and $h(x)=0$ define the inequality and equality constraints for the problem. A solution x^0 is Pareto optimal for the problem defined by Eqs. (3.D.1) and (3.D.2) if there exists no other solution x satisfying Eqs. (3.D.2) for which $f_i(x) \leq f_i(x^0)$ for $i=1,2, \ ,Q$, with $f_i(x) < f_i(x^0)$ for at least one objective criterion. In words, the solution x^0 is Pareto optimal if there exists no other feasible solution x which dominates it for all objective criteria.

The Pareto-optimal solution set is the set of solutions distributed along the Pareto-optimal surface defining the trade-off between the different objective criteria. From among a population of N solutions, the number P of solutions belonging to the Pareto-optimal solution set depends on the specific nature of the problem posed by Eqs. (3.D.1) and (3.D.2), and theoretically can be anywhere in the range of $1 \leq P \leq N$.