Towards a Systematic Methodology for the Design of Elevator Traffic Systems in High Rise Office Buildings

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Abstract. Elevator traffic system design has been traditionally based on rules of thumb and the designer's judgement and expertise. This is especially true for high rise buildings. This paper attempts to develop a systematic methodology for the design of high rise buildings, by the use of rational rules.

In order to ensure clarity and consistency, the paper defines the terms sector, zone and stack.

The systematic methodology is built around the use of rational rules. Rational rules differ from rules of thumb in a number of ways, and these are discussed in the paper. Six rational rules are presented and used in the design of elevator systems in high rise buildings. The rules are triggered by the checking of a number of design parameters such as the waiting time and the travelling time, as well as the core area used up and the number of elevators in the group. A simulator for incoming traffic and a single entrance is used in order to obtain the parameters for a design and then to trigger the rational rules.

Note: An earlier version of the paper has been sent out to a number of industry experts for their comments. Nine industry experts have provided detailed written commentary on the content of this paper. Their responses, as well as a detailed section of case studies, have been included in the final copy of this paper which has been sent to a peer reviewed journal for review and potential publication.

Nomenclature
AWT average waiting time in seconds
AQT average queue length in persons
ATT average travelling time in seconds

1 INTRODUCTION

Elevator traffic system design has been traditionally based on rules of thumb and the designer's judgement and expertise. This is especially true for high rise buildings. These are two examples of the general rules of thumb that are used:

- The number of floors in a single zone should not exceed 18 to 20 floors.
- Sky lobbies should be introduced for buildings exceeding 50 to 60 floors.

Other examples of simple rules of thumb that are used in the conventional design of elevator traffic systems can be found in [1]. There are three problems with the use of rules of thumb:

- They do not explicitly provide an explanation for the rationale underlying the rule to others, despite the fact that the designer who uses them does.
- Following on from the previous point, if the assumptions on which the rule was based change, the rule cannot be changed accordingly.
- Rules of thumb cannot be used to develop a systematic design methodology.

The aim of this document is to develop a set of rules that can guide the designers throughout the elevator traffic system design process for high rise buildings. Solely for clarification in this piece of work, a high rise building is defined as any building that has more floors than those that can be accommodated in a single zone (thus requiring multiple zones or a sky lobby, both of which are defined in section 2 of this document). The rules presented later in this paper present a methodology for deciding how many floors can be accommodated in one zone.

The rules will be based on rational reasoning, whereby the rationale on which the rule is based will be clearly stated. This ensures that where the underlying assumptions change, the rule changes accordingly. In addition, the rules are fully transparent showing the threshold values of the different parameters for the different rules. The designer can thus change these thresholds as he/she sees fit.

It will be assumed that the designer starts with a calculation that will provide a starting point for the simulation. The design process followed in this paper has been based on the methodology found in [2] and [3]. The round trip time calculation using equations has been based on the equations found in [4], [5] and [7]. Under certain situations, it is necessary to use the Monte Carlo simulation method to evaluate the round trip time [6] and the average travelling time [8]. The design process then moves to simulation in order to fine tune the design.

It will also be assumed that the designer possesses the required skills to carry out the design of a single zone elevator traffic system. The methodology for designing a single zone elevator traffic system is considered to be beyond the scope of this document. In effect, the design of a single zone elevator traffic system is the basic building block that will be re-used in all high rise building designs.

Section 2 introduces the terminology that is used to describe how the building is split into different units, such as sectors, zones and stacks. A clear terminology in this regard is essential for understanding the rest of this paper. Section 3 provides an overview of the work to date in the area of high rise vertical transportation system design. Section 4 emphasises a basic principle in using the rules that will be later introduced in this paper (namely that the rules are there to guide and aid the designer rather than present a final solution). Section 5 discusses the impact that destination group control will have on the design of vertical transportation system for high rise buildings. Section 6 introduces the concept of normalisation in the context of elevator traffic systems. The core of the paper is in section 7 which presents the six rules. Conclusions are drawn in section 8.

2 SECTORS, ZONES AND STACKS

No unanimous agreement exists in the industry on the exact definitions of the terms sector, zone and stack. In order to avoid any ambiguity, these terms are defined as shown below within this piece of work.

> *Sector*: A group of floors (usually, but not necessarily, contiguous) that are grouped together in the controller software and are served by one or more specific elevator(s). The allocation of a sector to one or more elevators and the sector's composition are not necessarily fixed and can be dynamically changed from one round trip to the next.
>
> *Zone*: A group of mostly contiguous floors that are served by a number of elevators operating in one group. The size and composition of a zone is fixed (e.g., location of the machine room) and cannot be altered. It is usually motivated by the need to reduce the average travelling time and the need to restrict the number of elevator cars in a group to eight or fewer. It results in a saving in floor area on the floors above the lower zone(s).

Zoning can be also be used as a tool for traffic segregation (e.g., hotel, offices, residential). A zone can contain a number of sectors.

Stack: A stack is formed when a number of zones are grouped together and served by a common sky lobby that channels the incoming traffic. The lowest stack is in fact served by the main entrance and does not require a sky lobby. A stack that is served by a sky lobby can be thought of as a building that has been placed inside another building. A stack can contain a number of zones.

An example of a chart that graphically illustrates the use of zones in the design of high rise buildings can be found in [9].

3 OVERVIEW OF EXISTING WORK ON HIGH RISE BUILDING TRANSPORTATION DESIGN

This section presents a general overview of the various contributions to high rise vertical transportation system design.

A good example of the detailed design of a high rise building (2 IFC in Hong Kong) has been presented in 2004 by To & Yip [10]. It has 88 floors and a population of 15,000. It has seven zones and two sky lobbies served by double deck elevators.

There are eight rules of thumb listed in To & Yip [10]. Some of these have been reproduced below:

1. The target handling capacity for the local zones shall be more than or equal to 12% and the target interval less than or equal to 30 seconds.
2. The target handling capacity for the shuttle systems shall be more than or equal to 15% and the target interval less than or equal to 20 seconds.
3. Top down sky lobby design systems are to be avoided.
4. There shall be no more than 8 elevators in each group.
5. The number of floors in a local zone should be around 15 floors.
6. The rated car capacity should be 1600 kg (20 persons).
7. The rated car capacity of double deck elevators should be 1600/1600 kg or 1800/1800 kg.
8. When used, a shuttle elevator shall serve no more than three local zones.
9. The passenger journey shall comprise no more than one transition between different elevator systems (e.g., a shuttle and then a local zone).
10. For each elevator that forms part of a local zone it shall serve no more than two floors (i.e. the ratio of floors to elevators in the local zone should be in the ratio of 2:1).

Jochem Wit [21] presents a number of building design examples on the use of destination group control to remove the need for zoning a building. Destination group control has been used as a means of segregating the different modes of traffic in the building.

In [9] it is shown that the two most important parameters that influence the design of a high rise building are the number of floors above the main entrance and the total population.

An expert system is described in Alexandris [11]. It uses forward and backward chaining inference mechanisms in order to accept or reject certain solutions. It has a set of if-then rules. An example of one of the rules is:

If passenger waiting time is more than 50 seconds then reject solution

Another rule uses natural language descriptions:

> If "loading is high" AND passenger waiting time is normal AND system cost is reasonable then accept solution.

He points out that a user would like to query the software as to how the decision was made for a certain design. He also discusses a rule base in which the user can modify or amend existing rules or add new ones.

In [12] Barney presents a general overview of vertical transportation systems in tall buildings. The paper contains clear definitions of low, mid and high rise, tall and very tall and skyscrapers. It also contains an excellent overview of the different arrangements of high rise design buildings (example: Petronas Towers).

Browne & Kelly [13] present an overview of the simulation carried out to assess the performance of the elevator traffic system for two of the buildings in the World Trade Center (destroyed in the attack of 11th September 2001).

Caporale [13] suggests normalising the average journey time (AJT) (25% of the 5 minutes, or 75 seconds). The reasoning for the five minute suggestion is not clear. The link might be the fact that five minutes is used as the basis for quantifying the arrival rate in a building (i.e., elevator systems in buildings are designed based on the expected arrival rate expressed as a percentage of the building population in the peak five minutes, denoted as AR%).

Fortune [14] states that the key to efficient high rise design is to stack the zones on top of each other. He also suggests that a two-minute headway should be achieved for the shuttle elevators. He also lists the seven technical problems that face any high rise design. He then outlines a general methodology for even going higher by effectively stacking buildings on top of each other (50 to 60 floor high buildings stacked on top of each other).

Howkins [16] classifies buildings further as follows:

- 40-60 floors denoted as tall buildings, of which many exist and can provide information and feedback.
- 60-80 floors denoted as very tall buildings, of which a good number exist and can provide information and feedback.
- 80+ floors denoted as super-high-rise buildings, of which not many exist (less than 20).
- 150+ floors denoted as super-high-rise/super-volume buildings, of which none exist at present.

Howkins [16] then:

- Calculates the actual core area and the lost potential rent from such an area.
- Presents a systematic procedure for designing elevator systems in high rise buildings.
- Suggests that the population density falls for high rise and tall buildings to a density much lower than 10 m^2 per person.

Mitric presents in [17] and [18] the concept of a total useful area in the building and presents a set of curves that peak at a certain arrangement.

Powell uses the term banking (meaning zoning) and uses dynamic programming to decide on the optimum arrangement. [19].

4 GUIDANCE TO THE DESIGNER RATHER THAN AUTOMATED DESIGN

It is not the intention of this piece of work to embed these rules into automated software that will complete the system design independently. The aim of this piece of work is to provide a set of rules that will be used to guide the designer throughout the design process. Judgement will be required at each stage by the human designer in accepting, rejecting or modifying the suggestions by the software.

For example, the designer could use a combined calculation and simulation software package that provides the outputs of the design process over a number of stages. At each stage, the software will issue notifications, warnings and suggestions to the designer. It is up to the designer to heed the warnings and then accept, reject or modify the suggestions. The design process then proceeds to the next stage.

5 EFFECT OF DESTINATION GROUP CONTROL

With the increased popularity of destination control systems, and as they become more of a standard feature in elevator group control systems, it is acknowledged that some of these rules will need to be amended. As an example, one of the rules presented later in this document uses the value of the average travelling time as a trigger for the introduction of multiple zones. However, in cases where all the design parameters are acceptable except for the value of the average travelling time, the use of destination group control could address this problem. In the long term, the use of destination group control could have a significant impact on the use of zones as well as their numbers. The use of destination control systems without resorting to zoning could lead to loss of floor space, but can be used as a future proofing insurance policy against changes in the building population or its use.

As can be seen in the discussion above on destination group control, the advantage of clearly stating the rationale underlying a rule makes the rules robust to changes in technology and current acceptable performance parameters (as opposed to the use of rules of thumb).

Jochem Wit [21] provides an interesting case study in which he uses a destination control system in a high rise building to segregate the different modes of traffic heading to different parts of the building (e.g., hotel, office, residential) with overall savings arising from the sharing the capacity of the elevators in the group.

6 PARAMETERS AND NORMALISATION

As will be seen in the next section, the antecedents (the first statement in the if-then rule) of most of the rules are based on checking one of the parameters of the elevator traffic design (e.g., number of elevators in the group) or one of the performance parameters (e.g., average waiting time). In the rules presented, the authors have assumed acceptable thresholds for these parameters (e.g., 90 for the average travelling time and 30 seconds for the average waiting time). These are subjective decisions, and others could use different parameters (e.g., the maximum value of the average waiting time) and different values for such parameters if desired. This is an advantage rather than a disadvantage and makes the use of the rules more flexible.

For the sake of completeness, the definitions of the average waiting time and the average travelling time assumed in this document are shown below:

- Passenger waiting time: The time from the arrival of the passenger in the lobby until he/she starts boarding the elevator (i.e., it does not include his/her boarding time). It is acknowledged that these differ from the ones in [22] which have been proposed by a number of industry experts.

- Passenger travelling time: The time from the start of the passenger boarding the car until he/she completes alighting at his/her destination. It is acknowledged that these differ from the ones in [22] which have been agreed by the industry.
- The average of each of the two parameters above is the average of the waiting time or travelling time of all the passengers in the simulation workspace, respectively.

Normalisation is a powerful tool that allows the generalisation of the rules across different buildings and different scenarios. One of the parameters that will be normalised in the rules introduced in the next section is the average queue length. It is meaningless to quote this as an absolute number and it makes more sense to normalise it by dividing it by the rated car capacity. The normalised average queue length represents the number of *car loads* waiting in the lobby on average, and is effectively a measure of the system performance.

Caporale suggest the normalisation of the average waiting time as a percentage of the five minutes design period (300 s).

7 THE RULES

This section presents the six main rules. Each rule also has some sub-rules. The rules that are used are crisp. The problem generally with crisp rules is that they have a clearly defined threshold, something that does not well reflect the way human experts think. It is hoped that these rules will be further developed in the future to fuzzy rules based on fuzzy logic.

Some of these rules are invoked at the calculation stage, while others are invoked at the simulation stage. Both the antecedent statement and the consequent statement are shown inside curly brackets. Where more than one antecedent is present, their relative strength is indicated inside square brackets.

7.1 Rule 1

This rule is effectively a trigger for zoning and appears at the calculation stage.

If

{the number of elevators is more than 8 for conventional group control (or 12 for destination control) [stronger antecedent]

and

the car capacity is more than 26 persons/2000 kg [weaker antecedent]}

then

{zone the building (or increase the number of zones if already zoned)}

It is also possible in some cases to use sectoring instead of zoning, offering more flexibility for the future, but leading to a loss of floor area.

The rationale for limiting the elevator car capacity is the fact that larger cars become very inefficient when passengers are boarding and alighting during a stop.

The rationale for limiting the maximum number of elevators in a group is to provide sufficient time for the passengers to get to the desired elevator through the crowded lobby in good time. A better (and more rational) expression of this rule would be to use the *passenger-to-elevator-lobby-travelling-time*, but little information is available currently on this detail.

7.2 Rule 2

This rule addresses the problem of excessive average travelling time (assuming all other parameters are acceptable). It is invoked during the simulation phase.

If
{the average travelling time is more than 90 s}
then
{zone the building (or increase the number of zones if already zoned)}

The reason for the limit of 90 s is based on passenger behaviour and tolerance to journey length. In general passengers are around twice as tolerant to travelling time as they are to waiting time.

The rule above assumes that conventional non-sectored group control is used in the simulation. It is also possible in some cases to use sectoring instead of zoning, offering more flexibility for the future, but causing loss in the floor area. This future proofs the elevator system in the building against future changes. The term sectoring is used here in its widest meaning, whereby destination group control is considered an advanced mode of sectoring.

7.3 Rule 3

This rule provides guidance to the user on the split of the building population between the various zones. It is invoked during the simulation stage.

When zoning, divide the population into the following percentages:
Two zones: lower zone, 57%, upper zone 43%.
Three zones: lower zone 43%, middle zone: 30%, upper zone 27%.
Four zones: 1st zone 29%, 2nd zone 27%, 3rd zone 22%, 4th zone 22%.

The rationale for this rule is to try to equalise the number of elevators in each group serving each zone. Preference is given to the following if possible:

- Equal elevators in each zone (for symmetry).
- An even number of elevators in each zone.

The calculation stage will assign appropriate speeds to the elevators in different zones (as for example where the *HARint* Plane methodology is used [2]). This is usually based on the rational requirement of travelling between terminal floors in less than 20, 25 or 30 seconds (accounting for acceleration, deceleration and jerk). The origins of the three suggested values are explained in the HARint Plane methodology paper [2]. Testing the three values could result in the reduction of the number of elevators, or optimising the speed depending on the results.

7.4 Rule 4

This rule is added as an extra check to ensure the adequacy of the car capacity that results from the calculation stage and is invoked at the simulation stage. The rationale for this rule is that the car loading sometimes needs to be increased under simulation from the value stipulated in the calculation stage. This is due to the random effects of queuing theory.

If

{all the following parameters are acceptable (number of elevators, car capacity, average travelling time)
and
the average waiting time is more than 30 s
and
the average queue length is more than the car capacity (or the normalised average queue length is more than 1)}

then

{increase the car capacity}

The antecedent of this rule uses the average waiting time and the average queue length, which in turn are heavily dependent on the value of the workspace (i.e., the period over which passengers are generated for the purposes of simulation). A typical value for the workspace is 900 s (15 minutes). More details about the effect of the workspace can be found in [23].

7.5 Rule 5

This rule can be used to invoke the use of double-deckers at the calculation stage.

If

{car capacity is very large (much larger than 26 persons, e.g., 48 persons)
and
the number of elevator in the group is acceptable}

then

{use double deckers}

The rationale for this rule is the saving in floor area which results from the use of a smaller number of double deck elevators compared to a larger number of single deck elevators.

7.6 Rule 6

Zoned systems discussed earlier can be referred to as *direct from ground* (DFG) systems, in which passengers have the luxury of being able to travel to their destination in one trip. The main rational driver for introducing sky lobbies is the loss of floor area, in addition to the physical limitation imposed by the fact that steel ropes place a limit on the maximum possible travel. Hence this rule uses the loss in floor area used by the elevator shafts, lobbies and machine rooms as a trigger for the use of sky lobbies.

The antecedent for this rule is the ratio of the net area to the area used by the elevators (shaft, lobby, machine room). When this ratio exceeds a certain value, then the building ceases to be feasible and sky lobbies must be introduced.

If

{the ratio of the *net area* to the *elevator area* exceeds 4 to 1 respectively}

then

{introduce sky lobbies}

This rule ensures that the building efficiency (net area to gross area) does not deteriorate. It could be based on a simple 10 m^2 net area per person and ISO 4190-1 areas for elevator shafts and machine rooms; but could be based on whatever information is available to the designer (e.g., population per floor). It has also been found in practice that it is difficult to introduce more than four zones in a building while still satisfying this area rule.

A fictitious building with progressively increasing numbers of floors (10, 20, 40, 50 and 60 floors) has been used to illustrate the ratio used in the antecedent in the rule. It can be seen that the threshold ratio of 4:1 is exceeded somewhere between 40 floor and 60 floors. The results are shown in Table 1.

Table 1 Areas taken by the elevators in five fictitious buildings using direct from ground (DFG) arrangements.

Number of floors above the main entrance	Net area: Area taken up by elevators (shaft, lobby and machine room):
10	13.7:1
20	8.8:1
40	4.4:1
50	3.77:1
60	3.18:1

Ear comfort due to change in pressure at high speeds and long distances could also be used as a secondary trigger for sky lobbies. It has been suggested that when the travel distance is more than 300 m and the speed is around 8 m/s a sky lobby is recommended in order to allow passengers to rest and adapt to the change in pressure.

8 CONCLUSIONS

This document has presented six rules that can be used to guide the elevator traffic system designer throughout the design process. It has been assumed that the design process proceeds in two stages: calculation and simulation.

It is not the intention to use the rules for automated design software, but instead to guide the designer through the design process by issuing notifications, warnings and suggestions.

The rules have been based on rational reasoning; with the obvious advantage that where the underlying assumptions change, the rules can be easily adapted to suit.

The rules guide the designer as to when to zone the building in order to reduce the average travelling time and in order to keep the number of elevators in the group below a pre-defined number. The rules also use the net areas to the elevator areas ratio as the trigger for the introduction of sky lobbies.

It is worth noting that all of the rules presented here are crisp rules. Crisp rules suffer from the problem of making a sudden change once a parameter has exceeded a threshold value. The use of fuzzy logic and fuzzy rules would be more appropriate and would better reflect the nature of human judgement in the design process.

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