Hospital lift system simulator: a performance evaluator-predictor[1]

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Abstract

Hospitals often experience lift congestion as a result of their heavy traffic, complex user types, and relatively slow-moving lifts (due to concerns over safety). Given the increasing number of current and new hospital building blocks that consist of many storeys, a visual simulation-based decision support system (DSS) is recommended. We present the modelling approach and development of a tool capable of being used for lift performance evaluation/prediction of existing/new hospital designs. These are also applicable to other general-purpose lift systems. A new data modelling approach, based on collected empirical traffic data, was developed to estimate the inter-floor passenger traffic. The DSS is flexible enough to allow the input of any zoning policy. The integrated zoning analysis offered here has not been found in existing lift simulators. This paper is the first to model a special feature designed to disable certain lift buttons in order to ensure fair use of the lift service. We carried out field studies of two existing hospitals, and we projected lift demand for a new hospital under construction. Performances at all three hospitals with different design structures under different operational control policies and lift features are given.

Keywords: Decision support systems; Health services; Simulation; Elevator performance

1 Introduction

This study was initiated by the local Hospital Authority of Hong Kong in view of the need to evaluate lift performances from lift users perspective since most local hospitals consist of high-rise buildings and are located in densely-populated areas. One of our goals was to objectively understand the current lift congestion level in existing hospitals. Our intention is to create better understanding between hospital managers and lift manufacturers. The latter group, given their focus on engineering design and their business priorities and need for confidentiality about the lift design, may not be willing to provide certain "what if" tools and techniques essential for hospital planning purposes. The deliverables of our work include techniques and objective tools that we use to explore alternative policies of lift control and different zoning policies for continuous improvement of the lift service. In the context of

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a yet-to-be-commissioned new hospital, the hospital planners intended to make forecasts of passenger traffic and to investigate the adequacy of lifts and future modes of lift operation. For this purpose, computer simulation was used due to its high modelling flexibility. The performance of different lift control and zoning policies can be evaluated more easily by using a simulation model. The model was integrated into a computer-based system in order to form a decision support system (DSS) to facilitate decision-makers in performing the "what if" analysis of lift systems. The development of such a decision support tool can be a useful performance evaluator/predictor of hospital lifts.

According to So (2000), simulation is the best method of obtaining an accurate prediction of elevator group behaviour under a full range of traffic conditions. Recent studies found in the literature indicate a trend of using a lift simulator as an off-line system to assist in data analysis and decision-making. Beard (1986) described an interactive network analysis simulation program, TRAM/NETSY, designed by the UK Department of Health specifically for nucleus hospitals (a standardized building template usually of two stories with a linear hospital street). It can help users analyse the expected flow among various departments. Galpin and Rock (1995) developed a lift simulation prototype with graphics and user interface that could be incorporated into lift simulation programs. Real passenger data are necessary for complete implementation of the simulation model. The lift simulator developed by Hamdi and Mulvaney (1998) can access real passenger data gathered from installed lift systems to establish models of passenger movements inside a lift system. However, real data relating to individual passenger movement (such as waiting time and system time) and the number of passengers waiting outside the lift were not available. The general case of all lifts visiting all floors was adopted in the simulator by Hamdi and Mulvaney (1998). The DSS Elevate, developed by Peters (1998), is available in the market as a development platform for elevator control and traffic analysis. A zoning option for high-rise buildings is available where certain floors served by the same lift group are only accessible by these lifts. However, a limitation is that each lift group can only be analysed separately. The impact of different lift groups on passengers cannot be simulated simultaneously. Passengers with a specific origin-destination need first to be sorted into the right lift group. When the zoning policy involves passengers' changing lift groups on some floors, the pre-processing of passenger traffic has to be done manually and so will take up a lot of time.

To complement the work of previous authors, we propose a new data modelling approach to estimate inter-floor traffic. Our DSS provides a distinct user-option of an integrated zoning policy that does not require the pre-processing of passenger data into relevant lift groups. This new feature is not found in current interactive lift simulators. In addition, we propose the modelling of another special lift control feature – the disabling of a certain up/down lift button(s) on a specific floor(s), which has not previously been considered in the elevator literature. This will force a lift to go in a particular direction to ensure that the lift service is available for all floors, especially during busy periods.

The remainder of the paper is organized as follows. Section 2 reviews the literature related to the development of our lift model. Section 3 describes the proposed demand model, the forecasting procedure, and our lift model. The interfaces of the different components of the DSS software are presented in Section 4. Section 5 describes the application of the model to two existing hospitals and a yet-to-be-commissioned new hospital. Concluding remarks are given in Section 6.

2. Literature review

As our work extends across many areas (demand modelling, lift scheduling policies, lift performance analysis, and zoning policies), in this section, we shall review a selected list of literature for each area covered.

2.1 Passenger demand modelling

Butcher and Wilson (pp. 3-2, 1993) pointed out that "the difficulty in planning lift installation is not in calculating its probable performance, but in estimating the likely passenger demand". There are various means of estimating lift passenger traffic as described in Peters *et al.* (1996). Lift designers may consult design guidelines such as those found in Butcher and Wilson (1993). The main focus is on commercial buildings. Passenger arrival rates to specific floors are expressed as percentages of the building's population. Traffic surveys have been published on selected building types. The busiest traffic in most building types was found to occur either during up-peak or down-peak periods. Inter-floor traffic, which is more significant in hospitals, depends upon building characteristics. Other means of estimating demand include manual surveys. Yet it is difficult to collect details of inter-floor traffic as this involves pedestrian tracking. Pedestrian tracking is possible with computer vision, yet accuracy depends on image processing capability, and errors when tracking people are still unavoidable. Since data collected are always limited and subject to sampling errors, we propose a smoothing method to reduce inaccuracies.

2.2 Lift scheduling policies

Much effort has been devoted to the design of better lifts or to improving operating policies. Butcher and Wilson (1993) and Strakosch (1998) described various aspects of lift design and general guidelines. Strakosch (1998) considered important factors on the general design of hospital lifts. Shearn (1983) derived the optimal stopping strategy for a single lift by minimising the total passenger travel time outside the lift. Benmakhlouf and Khator (1993) determined the best operating strategies for four lifts under different levels of traffic intensity by using minimum passenger time measures. The logic of the real-time lift controller, a complicated part of lift design, varies among lift manufacturers and is usually kept confidential. In our DSS, the information required to simulate the controller was obtained by interviewing the lift manufacturers.

2.3 Lift performance analysis

Analytical lift traffic models and derived lift performance measures (e.g., round trip time, number of stops, and number of passengers per trip) are covered comprehensively in Barney and Santos (1985) and Barney (1986). The predictability of mathematical models in this context relies on the simplifying assumptions made about the passenger movement. Factors in the physical environment are often not considered.

Simulation is frequently used to validate analytical results. Both analytical and simulation techniques can complement each other. Ladany and Hersh (1979) used simulation to examine various elevator-operating schemes for a commercial building. Passenger arrivals were assumed to follow the Poisson process. Siikonen (1993) found close agreement between theoretical and simulated measures of car interval (the time between arrivals of two consecutive lifts on a floor) and the load carried, respectively. However, simulation results showed no direct relationship between passenger waiting times and car interval, which has often been assumed in analytical models. The former is highly dependent upon traffic patterns and the call allocation algorithm. Lustig (1986) suggested using both the tools of data logger and simulation for cross-validation and to improve the lift system design. When determining the parking floor for a free lift where no mathematical formula and models exist, Tam and Chan (1996) collected real data and applied simulation modelling. Obviously, simulation should be used as a better performance evaluator than an optimiser when the complexity of a system and the number of decision variables increase.

2.4 Zoning policies

Galpin and Rock (pp. 269, 1995) pointed out that "it would be useful to be able to specify a particular allocation of floors to zones and evaluate the lift performance in terms of this". Zoning policies can be classified into static zoning or dynamic zoning. Static zoning refers to the permanent assignment of a group of lifts to service a number of floors in a building. Temporary static zoning can be pre-scheduled during certain times of the day. So and Chan (1997) presented a dynamic zoning model that involves partitioning the floors into a number of zones, each consisting of a group of consecutive floors, in order to minimise cost functions involving variances in the equivalent round trip times among all lifts. An assumption is that all inter-floor passengers travel to the main terminal (the only common floor for all zones) to change lift groups. Apart from the main terminal, the zones are nonoverlapping blocks. Zoning policies employed in practice are usually relatively simple and involve at most two floors for changing lifts. As mega-high-rise buildings become more common nowadays (Fortune, 1997), the complexity of zoning policy and the number of floors used for changing lifts increase. Godwin (1993) described a case of zoning design for a high-rise office building in Frankfurt that was based on the building's design rather than on conventional elevatoring solutions provided by lift manufacturers. It is indeed important to involve the user in capacity planning for lifts as well as in decisions regarding appropriate operating modes.

Our work describes a more complete model for lift traffic analysis, considering passenger characteristics, the functional capacities of the building, and lifts' engineering design. As well as applying the model to three local hospitals, we are currently working on a similar project for an existing hospital scheduled for redevelopment and expansion.

3. Model Development

Performance measures, the modelling of passenger traffic, and the forecasting of lift traffic for a new hospital are described in the first three subsections below. (Forecasting in particular requires close co-operation with the hospital's management in order to reach appropriate traffic assumptions about the different hospital functions.) The lift system design and zoning policies are presented in the remaining subsections.

The hospital lift simulator (HLS), intended for different hospitals using different operating modes, is designed as shown in Figure 1.

[Insert Figure 1: Hospital lift simulator (HLS)]

The input parameters of the simulator are as follows:

- Lift data – number of lifts; lift capacity (maximum number of persons assuming a load of 150lb each); door time; door dwelling time (estimated overhead time incurred in addition to the door time before a lift moves, possibly caused by reopening or closing of doors due to new arrivals, etc.); start-up acceleration (acceleration undertaken when the lift starts to move from its idle state); maximum acceleration; start-up time (time taken by lift to reach maximum acceleration from its start-up acceleration); maximum speed
- Lift features – call assignment logic (assignment criteria of calls in the system to lifts); parking level (floor to park on when no call is assigned); full load bypass (bypass external calls when the current load exceeds a specified percentage of the lift capacity); up-peak (assign lift(s) to serve the heavy up-trip traffic on the main floor

when a recently departed lift experiences a load beyond a specified percentage of capacity limit); longest-wait (bypass external calls to serve a floor with an external call activated for more than a specified time limit); failure rate (the probability of lift failure); downtime duration (expected duration of lift failure)

- Zoning policy – allocation of lift(s) to serve only particular floors; disabled buttons (forbid the use of certain up/down call buttons on some floors to ensure traffic on extreme floors can be served)
- Building data – number of floors; floor separation distances
- Loading data – unit load (basic unit of the lift capacity: space requirement for a single person in the lift; other traffic types such as beds take up multiples of the unit load); loading/unloading time (time for a person to enter/leave a lift); "blind" probability (likelihood of a lift user activating both up and down buttons for convenience); origin-destination matrix (floor to floor traffic)

The input parameters are provided either by the lift companies of the existing hospitals or the hospital management, or are based on data collected in the field studies.

In a hospital environment, common types of lift users include passengers (classified as staff and visitors), wheel chairs, trolleys, and beds manned by staff. As each type has different space occupancy and loading time, the space utilisation (expressed in the number of unit loads) and the typical loading time of each type are estimated.

3.1 Performance measures

The performance statistics generated by the simulator are classified into three groups: time, space, and utilisation, as shown in Table 1. They represent a quantitative performance of passenger experience, system efficiency and effectiveness, and level of lift congestion.

Table 1

Performance measures

Time	Space	Utilisation
• Passenger waiting time • Passenger riding time • Passenger system time (= passenger waiting time + passenger riding time) • Lift response time*	• Number of passengers waiting in lobby • Number of lift users originating from individual floors	• Proportion of "busy time" of lift • Number of passengers in lift

*Lift response time is the time that elapses from when the first passenger activates the floor button until the first lift arrives.

One of the interests of hospital management is investigating if there is any difference between the lift response time available from the data logger and the passenger waiting time derived from simulation. When traffic is light, the passenger who first activates the lift button will experience a level of waiting time equal to that of the lift response time. The passengers that arrive before the lift opens will experience a shorter waiting time. On the other hand, when traffic is heavy, those passengers arriving late may not be able to enter the first lift if it is full. Thus, their waiting time could be longer than the lift response time. Lustig (1986) compared results from simulation and from data logger for a 29-floor building and found that they were nearly identical. Whether such observations can be generalized to other buildings and levels of traffic intensity is a question that should be investigated.

3.2 Inter-floor traffic model

For most buildings, either up-peak or down-peak traffic was dominant. Survey results for a major high-rise hospital building in Peters *et al.* (1996) indicated a significant level of inter-floor traffic. We propose an alternative approach in modelling inter-floor passenger traffic.

In the literature, Poisson distribution for passenger arrivals (Benmakhlouf and Khator, 1993; Ladany and Hersh, 1979; Siikonen, 1993; Sweet and Duket, 1976) or uniform distribution (Barney, 1986) is often assumed. As hospitals have different building structures and lift user types are more complex, Poisson arrivals should not be naturally assumed but empirical data should be used. We carried out field studies for two existing hospitals. The traffic data were collected from the lift lobby as well as from inside the lift. Some data, such as those relating to the arrivals at and departures from a lift lobby on different floors, were collected in the lift lobby. Inter-floor traffic data cannot be directly obtained from a lift lobby, so observers inside the lift were assigned to note the floors of origin and destination of lift users. The in-flow and out-flow data obtained can then be used as weights to derive an estimate for the inter-floor demand that occurs less frequently. The essential data collected are classified into two groups:

- in-flow, $p_i(t)$, and out-flow, $q_i(t)$, of floor i in time interval t, expressed in terms of the number of lift users;
- number of lift users, $n_{ij}(t)$, recorded in the lift during time interval t, entering the lift on the ith floor, and exiting on the jth floor.

Here, t denotes the short time interval within the time block of interest (e.g., the morning peak period from 8:30 – 9:30 could be divided into six 10-minute intervals). The origin-destination matrix of the loading data represents inter-floor traffic, m_{ij}, expressed in terms of the number of lift users, during the entire time block between origin i and destination j, for all floor pairs (i, j). As some inter-floor traffic may not occur frequently, m_{ij} is estimated from the field data $\{p_i(t), q_i(t), n_{ij}(t)\}$ as described below. The proposed approach is based on estimates from the in-flow/out-flow traffic data collected on different floors. The average level of inter-floor traffic will then be estimated from the relative ratio of $\{n_{ij}(t)\}$, weighted by the in-flow and out-flow data. In steps 1-3 below, we first estimate the inter-floor traffic, m'_{ij}, from all lift user demand departing from the ith floor, $\{p_i(t)\}$.

Step 1: Estimate the proportion of total demand at floor i, $r_{ij}(t)$, departing to the jth floor at time t.

$$r_{ij}(t) = \frac{n_{ij}(t)}{\sum_k n_{ik}(t)} \tag{1}$$

Step 2: Estimate the weighted relative ratio of demand, $\overline{r_{ij}}$, departing from the ith floor to the jth floor over the entire time block. The weight selected is proportional to both the in-flow on the ith floor, $p_i(t)$, and the out-flow on the jth floor, $q_j(t)$. (The sum of the weights equals one.)

$$\overline{r_{ij}} = \sum_t \frac{p_i(t)\, q_j(t)}{\sum_u p_i(u)\, q_j(u)} \cdot r_{ij}(t)\,, \tag{2}$$

where the index u denotes all the short time intervals within the time block of interest.

Step 3: Estimate the mean demand, m'_{ij}, departing from the ith floor to the jth floor over the entire time block.

$$m'_{ij} = \sum_t p_i(t) \cdot \frac{\overline{r_{ij}}}{\sum_k \overline{r_{ik}}} \tag{3}$$

In steps 4-6, which are analogous to steps 1-3, we estimate the inter-floor traffic, m''_{ij}, from all demand arriving at the jth floor, $\{q_j(t)\}$.

Step 4: Estimate the proportion of total arrival demand at floor j, $s_{ij}(t)$, originating from the ith floor at time t.

$$s_{ij}(t) = \frac{n_{ij}(t)}{\sum_k n_{kj}(t)} \tag{4}$$

Step 5: Estimate the weighted relative ratio of demand, $\overline{s_{ij}}$, arriving at the jth floor from the ith floor over the entire time block. (The weight chosen is the same as that chosen in *Step 2*.)

$$\overline{s_{ij}} = \sum_t \frac{p_i(t) q_j(t)}{\sum_u p_i(u)\, q_j(u)} \cdot s_{ij}(t)\,, \tag{5}$$

where the index u denotes all the short time intervals within the time block of interest.

Step 6: Estimate the mean demand, m''_{ij}, arriving at the jth floor from the ith floor over the entire time block.

$$m''_{ij} = \sum_t q_j(t) \cdot \frac{\overline{s_{ij}}}{\sum_k \overline{s_{kj}}} \tag{6}$$

Step 7: The origin-destination demand, m_{ij}, from the ith floor to the jth floor over the entire time block is estimated by the average of m'_{ij} and m''_{ij}.

$$m_{ij} = \frac{m'_{ij} + m''_{ij}}{2} \tag{7}$$

Once the inter-floor demand $\{m_{ij}\}$ is estimated for a time block, the arrival times of lift users will be uniformly distributed within the simulation period. The total number of arrivals is fixed and equal to the mean $\{m_{ij}\}$ pro-rated over the simulation period.

3.3 Demand projection model for a new hospital

Hospital traffic is more complex than traffic in commercial buildings as hospital buildings comprise various functional departments/wards. Godwin (pp. 254, 1993) pointed out that "frequently the building design drives the 'elevatoring' solution, very rarely is the reverse true". Finding an existing hospital that is identical to a new hospital in order to evaluate demand projection is almost impossible since the number of floors, facility layout, and functional capacities are normally quite different. The traffic forecasts for a new hospital are based on a function-to-function match with an existing hospital offering a similar set of services. Depending on how the service capacity of a function is characterised (e.g., by the number of beds, the number of examination rooms, or the daily number of places offered), the corresponding function in a new hospital will have its traffic estimated on a pro-rata basis from an existing one. In case no existing hospital offers a similar set of services, traffic among major functions in the new hospital will have to be estimated by experts. For example, the actual daily attendance of outpatient clinics and the usual route of their patients can be used to prescribe the corresponding traffic.

Firstly, the traffic flow data (subsection 3.2) need to be collected from field studies of the existing hospital. The floor plans (with functional capacity) of both the existing and the new hospitals, denoted by H_E and H_N, respectively, should be available from the hospitals' management. The demand projection can basically be classified into four groups as illustrated below.

(i) For example, functional capacity is characterised by the number of beds (e.g., medical wards or the Intensive Care Unit):

		In-out flow	Number of beds	
Function	Location in H_E	to function at H_E	H_E	H_N
Paediatric Ward	5th floor	$[p_5(t), q_5(t)]$	60	52

Estimated in-out flow to Paediatric Ward at H_N = [(52/60)·$p_5(t)$, (52/60)·$q_5(t)$)]

(ii) For example, functional capacity is characterised by the number of examination rooms (e.g., outpatient day clinics or the Occupational Therapy Department):

Function	Daily attendances in function at H_E	Number of examination rooms H_E	H_N
Psychiatric Clinic	65	6	4

Estimated in-flow to Psychiatric Clinic at H_N =

(4/6) · 65 · (simulation period / daily working hours) = estimated out-flow

(iii) For example, functional capacity is characterised by the number of places offered (e.g., day treatment centres such as the Day Medicine centre or the Day Geriatric centre):

Function	Actual daily number of places offered at H_N	Estimated number of accompanying relatives per patient at H_N
Day Surgery	20	2

Estimated in-flow to Day Surgery at H_N =

20 · (1+2) · (simulation period / daily working hours) = estimated out-flow

(Note that this estimation is simply prescribed by the hospital's management and does not involve traffic data collected in H_E.)

(iv) For example, similar functions are often grouped close together:

Functions	Location in H_E	In-out flow to functions at H_E
Physiotherapy Department	8th floor	[$p_8(t)$, $q_8(t)$]
Speech Therapy Department	9th floor	}[$p_9(t)$, $q_9(t)$]
Dietetics	9th floor	

The same set of three functions is grouped on the same floor in H_N. Hence, the estimated in-out flow to these functions at H_N = [$p_8(t) + p_9(t)$, $q_8(t) + q_9(t)$].

Categories in (i) and (iv) could be upper bound estimations for the in-out flow if the corresponding floor in H_N consists of other functions as well. Traffic estimation for other functions can be similarly derived. Finally, the in-out flow per floor can be obtained by summing up the flow for individual functions on the same floor. The inter-floor traffic estimation for H_N is then based on the approach described in subsection 3.2.

3.4 Modelling the lift system

A lift system basically consists of a set of lift cars controlled by a "controller". The controller schedules the assignment and dispatch of the controlled lift cars to serve the internal and external requests. Each lift car has a built-in automatic control system to drive itself into motion upon receiving the assignment from the controller. The characteristics and performance of the lift system depend heavily on the controller's design. Lift manufacturers are normally unwilling to release details of the actual design of their controllers. The controller in our simulator reschedules the lift assignment based on the loading and the current system states whenever it is activated at particular points, as illustrated in the overall view of the HLS algorithm (Figure 2). For the controller to schedule the lifts in the system, two types of system states are defined in the model:

- Loading request: internal and external lift calls
- Lift status: operational mode, call assignments, current loading, and information related to lift operation

[Insert Figure 2: Algorithm of the HLS]

The system states are updated from time to time. This process is triggered by the lift passengers and the lifts (due to new call arrivals, changes of lift movement, or lift status, etc.). To make call assignments to lifts during peak periods, those lifts which currently have special assignments are first identified and excluded. (These are lifts with the special lift features of full load bypass, up-peak, or longest-wait (see Section 3) being activated). For the remaining lifts in each lift group, the nearest lift is dispatched to serve calls according to a certain predetermined order. In the simulation, the special lift features can be activated or deactivated as selected by the user in the input.

The operating procedure of the lift controller is modelled and expressed below as pseudo-codes:

Operating procedure of the lift controller

Step 1: Reset all existing assignments to null for rescheduling.

Step 2: Identify lifts which are currently overloaded, loading passengers, in failure mode, or responding to the up-peak signal. Exempt them from rescheduling (i.e., the following steps).

Step 3: For each lift (not exempted in *Step 2*) do

Set the internal stop as the nearest internal call.

Initialise the internal stop as the lift's next stop.

next

Step 4: For each lift group (i.e., lift(s) serving the same set of floors) do

Find among the accessible floors within its group, the one that has recorded the **longest wait** (exceeding the threshold) with no current lift assignment. Assign the nearest empty lift (if any).

next

Step 5: If the **up-peak** signal is triggered, assign the nearest empty lift (if any) to the ground floor.

Step 6: For each lift group do

Identify external calls on its extreme floors; i.e., the lowest floor with an up call and the highest floor with a down call.

Assign an available empty lift (in the group) nearest to both extreme calls.

For each of the other external calls do

Assign the nearest available lift (in the group) with the same direction as the call direction.

next

next

Step 7: For each lift do

If no internal or external call is received, then assign the lift to its parking floor.

else

Set the next stop as the nearer of its internal stop and external stop.

Set the service direction as the call direction.

next

In order to make call assignments or to update system state changes, the information of every lift in motion needs to be known. The lift movements along the path to some destination floor (distance, speed, and acceleration along this path) are arrived at simply by using calculus. The four basic input lift data are start-up acceleration a_0, maximum acceleration $a_{\max}$, start-up time t_0, and maximum speed $v_{\max}$. These data were obtained from a lift company serving an existing hospital. A more complete set of equations describing the profiles of jerk, acceleration, velocity, and distance with respect to time can be found in Peters (1996).

In the simulator, we need a time function to be used in a subroutine in order to find the nearest lift to dispatch to the specified floor. It is derived from the inverse of the distance-time function. Given that a lift, starting from rest, is assigned to stop at some destination s_d metres from its origin, the profile of the lift movement depends on whether or not the destination floor is far away enough for the system to attain the maximum speed $v_{\max}$. These situations are classified as *Case 1* (maximum speed would be attained) and *Case 2* (maximum speed would not be attained), respectively. To enable calculation of the time taken to cover distance s ($0 \le s \le s_d$) on this path, critical break points, such as the distance covered during the start-up time (s_0), the time taken to reach the maximum speed (t_c), and the corresponding distance covered (s_c), need first to be determined. Results from these parameters and the time function $t(s)$ are stated simply as follows. (We refer the reader to Appendix A for the lift profiles and the proofs of the following results.)

$$\boldsymbol{s}_0 = (\boldsymbol{a}_{\max} + 2\boldsymbol{a}_0) \cdot \boldsymbol{t}_0^2 / 6 \tag{8}$$

$$\boldsymbol{t_c} = \left[(\boldsymbol{a}_{\max} - \boldsymbol{a}_0) \cdot \boldsymbol{t}_0 + 2\boldsymbol{v}_{\max}\right] / (2\boldsymbol{a}_{\max}) \tag{9}$$

$$\boldsymbol{s_c} = \left[(\boldsymbol{a}_{\max} - \boldsymbol{a}_0)(\boldsymbol{a}_{\max} + 3\boldsymbol{a}_0) \cdot \boldsymbol{t}_0^2 + 12\boldsymbol{v}_{\max}^2\right] / (24\boldsymbol{a}_{\max}) \tag{10}$$

Case 1 (maximum speed $v_{\max}$ would be attained, or equivalently, $s_d \geq 2\, s_c$)

$$t(s) = \begin{cases} 0 & s = 0 \\ \infty & 0 < s < s_0 \\ \left[3(a_{\max} - a_0) \cdot t_0 + \sqrt{72a_{\max} \cdot s - 3(a_{\max} + 3a_0)(a_{\max} - a_0) \cdot t_0^2}\right] / (6a_{\max}) & s_0 \leq s \leq s_c \\ t_c + (s - s_c)/v_{\max} & s_c < s \leq s_d - s_c \\ t(s_d) - t(s_d - s) & s_d - s_c < s \leq s_d - s_0 \\ \infty & s_d - s_0 < s < s_d \\ 2t_c + (s_d - 2s_c)/v_{\max} & s = s_d \end{cases} \tag{11}$$

(When the lift is starting up or decelerating, it does not have sufficient time to stop at the specified point (of distance s away); hence, the time taken is set to infinity for ($0<s<s_0$) and ($s_d - s_0 < s < s_d$).)

Case 2 (maximum speed $v_{\max}$ would not be attained, or equivalently, $s_d < 2\, s_c$)

$$t(s) = \begin{cases} 0 & s = 0 \\ \infty & 0 < s < s_0 \\ \left[3(a_{\max} - a_0) \cdot t_0 + \sqrt{72a_{\max} \cdot s - 3(a_{\max} + 3a_0)(a_{\max} - a_0) \cdot t_0^2}\right] / (6a_{\max}) & s_0 \leq s \leq 0.5s_d \\ t(s_d) - t(s_d - s) & 0.5s_d < s \leq s_d - s_0 \\ \infty & s_d - s_0 < s < s_d \\ 2\,t(0.5\,s_d) & s = s_d \end{cases} \tag{12}$$

3.5 Zoning policy

In a zoning policy, the entire set of floors is divided into a number of "blocks" with a designated lift group (a set of lifts) serving each block. Each lift group requires a separate controller for call assignments; thus, lifts in a lift group work independently of those in other lift groups. The purpose of zoning is to increase the lift system handling capacity. The criterion of dividing floors into blocks and allocating lift groups to blocks is often based on management policy, as it may be preferable for floors with certain major functions (such as outpatient clinics and day care services) to be accessible by more lifts. It is the intention of the Hospital Authority to use the DSS to evaluate various sensible zoning policies (where some floors may be served by more lifts) at different hospitals. For certain important functions (such as operating theatres), patients will be transported by patient lifts (located in a separate lobby and with specific service schedules) due to priority given to these patients and their hygienic requirements.

When considering a zoning policy as one of the user-inputs in the DSS, one of the difficulties lies in finding a feasible and appropriate path efficiently for each of all possible origin-destination pairs. Each of these paths may involve switching on some floors, as certain floors may be inaccessible by a lift group. When the zoning policy changes, this path may change accordingly. Past studies have not reported on this route-finding feature required for each origin-destination pair under general zoning policies, probably because the zoning policies adopted are relatively simple.

To determine the changeover floor(s) for any origin-destination pair, the shortest path algorithm (Dijsktra, 1959) is applied on a specially constructed network based on the selected zoning policy. We assume that lift users make rational decisions. On reaching a changeover floor, time measures for a passenger are updated in the simulation, and the next target floor and lift group to be used are generated by the algorithm. This procedure repeats itself until the destination floor is reached.

Consider the example of a building with six floors (denoted by floor 0,…, floor 5, where floor 0 represents the ground floor) and two lift groups (A and B). The zoning policy selected is to assign floors 0, 1, 2, and 4 to be served by lift group A; and floors 0, 1, 3, and 5 to be served by lift group B. The network constructed for this zoning policy is shown in Figure 3. A node, say *ig*, represents that floor $i \in \{0,\ldots,5\}$, which is accessible by lift group $g \in \{A, B\}$. An arc between two nodes represents either the corresponding floors, which are directly connected under the same lift group (e.g., (1A, 2A)), or the changeover of the lift group on a common floor (e.g., (1A, 1B)). The length l of the arc for node pair (ig, $i'g'$) in the network is given by:

$$l_{(ig,i'g')} = \begin{cases} (\text{travel time between floor } i \text{ and } i') + S & \text{if } i \neq i' \text{ and } g = g' \\ W & \text{if } i = i' \text{ and } g \neq g' \\ \infty & \text{otherwise} \end{cases}, \qquad (13)$$

where S represents the time incurred in passenger loading/unloading, and W is the waiting time for the next arriving lift on a changeover floor. S is an arbitrary time penalty imposed for stopping on a floor served by a lift group. This will model the passenger behaviour of choosing a lift with as few stopovers as possible. Similarly, W is an arbitrary time penalty (> S) imposed for changing lift groups. Dijsktra's algorithm can now be applied to find the shortest path (indicating changeover floor(s) and lift group(s)) for any origin-destination pair.

[Insert Figure 3: The zoning policy's network for finding the changeover floor(s) and lift group(s) by Dijsktra's algorithm]

Disabling certain (up/down) lift buttons on some floors is an alternative control policy explored by some hospitals, of enabling lifts to serve traffic on floors at either extreme. According to the experience of hospital staff, once an upward travelling lift becomes fully loaded with down-trip passengers, the lift will start descending and neglect traffic on the upper floors. If the "down" button of some lift groups on a mid-level floor is disabled, the lift system will divert the traffic towards using other lift groups. Hence, the lift group with the disabled "down" button will have spare capacity when it reaches the upper floors. This lift control feature has also been observed in some local residential and multi-purpose buildings where single-direction lift buttons exist on certain floors. The modelling of this lift control feature has not been addressed in previous studies. This additional feature could be incorporated into the zoning policy. The (undirected) network in Figure 3 can be modified by converting it into an asymmetric network and deleting certain arcs of forbidden flow. For instance, if the "down" button on floor 3 is disabled, then all down-trip passengers on this floor must go up to floor 5 before they come down. The network is modified as shown in Figure 4. Node 3B can now only allow an upward flow. The arc lengths would be defined as they are in equation (13). Dijsktra's algorithm could then be applied as before.

[Insert Figure 4: The zoning policy's network of disabled "down" button on floor 3]

4. A simulation-based decision support system

Here, we shall describe the different interfaces of the simulation software. The DSS is divided into two modules, which are each further subdivided into several components as shown in Figure 5:

- Simulation module: loading generator, lift simulator, and report writer
- User interface module: input interface and output interface

[Insert Figure 5: Simulation software]

The simulation module functions to simulate the operation of a lift system and to capture operational data in order to produce performance statistics given a set of input parameters (see Section 3). Interfaces are provided with which the user can input the parameters. Samples of the input interface are shown for the loading data (Figures 6 and 7), for the lift data and lift features (Figure 8), and for the zoning policy (Figure 9). In this sample, the lift system has five types of users. It consists of six lifts and the lifts are divided into two block zones to serve 10 floors (basement B1 to 8/F). The zoning policy is a typical lower/upper floor zoning with the two zones interchanging at the floor 4 (4/F). A loading generator is written to generate the passenger arrivals in a format acceptable to the lift simulator.

During the simulation, an animated display is shown as in Figure 10. The user can adjust the running speed on screen as desired. Three types of data are logged as indicated in the flowchart of the HLS algorithm (Figure 2):

- Continuous data – These data are logged periodically. They are related to the internal system states and are dynamically changing; e.g., the number of passengers in a lift.
- Check-point data – These data are logged whenever a particular state change occurs. They can be collected only during a change of state; e.g., the system times and waiting times of a lift passenger are logged upon exit from the system.
- Arrival data – These data are summaries of the system loading and are collected after the (passenger traffic) loading generation.

Time series data are captured and summarized by the report generator to produce various types of lift performance statistics (subsection 3.1). The user can choose to view a partial or full report from a set of options. The loading generator and report writer were written in the C++ programming language, while the code on the lift simulator was programmed in a simulation package MedModel (a simulation software developed by ©ProModel Corporation for health care applications). The programs for the input and output interfaces were written in Borland C++ OWL 5.0 (a C++ programming class developed by ©Borland) to be run on Windows 95 or above.

[Insert Figure 6: Loading data – parameters]

[Insert Figure 7: Loading data – inter-floor traffic (visitors)]

[Insert Figure 8: Lift data and features]

[Insert Figure 9: Zoning policy]

[Insert Figure 10: Animated display of a simulation run]

5. Case studies

The application of the DSS to three local hospitals will be described in three subsections in this section, respectively. Two hospitals with heavy lift traffic were selected in order to study lift operation improvements. They are referred to as hospitals A and B. Using the projected demand from one of the existing hospitals (A or B), we investigate the lift operational policies for a yet-to-be-commissioned new hospital referred to as hospital C.

The first priority of the hospital's management is passenger lifts, as they are for the use of both public and staff. Patient and cargo lifts are not considered in this study. (They usually serve specific functions (e.g., transporting patient meals) and are located in a separate lift lobby. These lifts either have specific service schedules or are manned by an internal operator equipped with a portable phone. If required, one can prescribe these scheduled services in the loading data file and examine the performances generated by the DSS.)

5.1 Performance evaluation of hospital A

Hospital A consists of an 18-floor building (three basement floors, B3–B1; the ground floor; 1st floor,…, 14th floor, denoted by G/F, 1/F,…, 14/F, respectively) served by four passenger lifts. Preliminary field studies were conducted in the morning, early lunchtime, late lunchtime, and the afternoon on weekdays in order to identify the peak period. We then focused our effort in the peak period, which was the late lunchtime period, in order to collect more data. This finding is supported by Peters *et al.* (1996) who also observed that the waiting time is longer during lunchtime than during a morning up-peak period, as the combination of passengers travelling up and down the building results in more stops per round trip.

From our data collected over 18 days at hospital A, it can be seen that significant extreme floor traffic existed on both upper and lower floors during the late lunch time peak period (13:50 – 15:30). A non-zoning policy was adopted by hospital A in the past. In response to staff concerns about the long waiting time experienced on the upper floors, the hospital's management had disabled the "down" buttons on certain upper floors (10/F–13/F). A lower/upper floors zoning policy was under consideration. Two lifts were arranged to serve the lower floors (B3–9/F) and the upper floors (B3–1/F, 9–14/F), respectively, with common changeover floors on B3–1/F and 9/F.

Earlier meetings with the hospital's management had raised the issue of comparing the lift service experienced by passengers (waiting times) with the logged response times of the lift system. The following four operational scenarios were proposed:

Table 2

Proposed scenarios in hospital A for evaluation by the DSS

Scenario	Zoning policy	Special lift features
1	Non-zoning	• full load bypass (90% capacity) • longest-wait (time limit: 15 min.) • up-peak (60% capacity from G/F)
2	Lower/upper floors zoning • lift 1, 2: B3 – 9/F • lift 3, 4: B3 – 1/F, 9 – 14/F	(Same as Scenario 1)

3	Lower/upper floors zoning (no B3 access for the upper-floors lift group) • lift 1, 2: B3 – 9/F • lift 3, 4: B2 – 1/F, 9 – 14/F	• full load bypass (90% capacity) • longest-wait (time limit: 15 min.)
4	(Same as Scenario 3)	• full load bypass (90% capacity) • longest-wait (time limit: 15 min.) • disabled "down" buttons on 7, 8, 11, and 13/F

Each scenario in Table 2 was run for 40 replications. The results are summarised in Table 3. For model validation, the average lift response time (1:16 min.) for the non-zoning policy (Scenario 1) obtained from simulation is close to the logged response time (1:28 min.).

The results shown in Table 3 indicate that implementing the upper/lower floors zoning policy (Scenarios 2 – 4) leads to a somewhat longer average waiting time than occurs when implementing the non-zoning policy (Scenario 1). However, the average lift riding time is reduced substantially, especially for higher-floor passengers. Detailed results by floor reveal that zoning with cancellation of the up-peak feature and removal of B3 from the upper-floors lift group (Scenario 3) also benefited the higher floors at the expense of the mid-level floors. Disabling the "down" buttons on certain upper floors (Scenario 4) improves time measures for up-trip passengers and down-trip passengers on some upper floors. Passenger waiting times are similar to or slightly less than the lift response times. This finding implies that the traffic demand is manageable under all scenarios. Other congestion and utilization measures are given in Table 3.

Table 3

Performance measures (averages) in hospital A

Scenario	Time measures (min.: sec.)				Space measures		Utilisation measures				
	Waiting time	Riding Time	System time	Lift response time	No. of waiting passengers in lobby (max.)	No. of lift users originating from a floor (max.)	Proportion of lift time (%)				No. of passengers in lift
							travelling	loading	unloading	idle	
1	1:11	1:11	2:22	1:16	0.39 (G/F: 14.38)	49.82 (G/F: 126.84)	57.5	27.7	13.8	1.0	3.33
2	1:33	0:49	2:22	1:39	1.15 (G/F: 14.38)	49.78 (G/F: 126.52)	57.5	27.5	14.2	0.8	3.37
3	1:32	1:09	2:41	1:38	1.18 (G/F: 14.32)	49.82 (G/F: 126.65)	57.4	27.6	14.1	0.9	3.44
4	1:29	1:12	2:41	1:30	1.16 (G/F: 13.73)	49.78 (G/F: 126.62)	55.8	28.1	15.4	0.7	3.49

Table 4

Performance measures (averages) in hospital B

Scenario	Time measures (min.: sec.)				Space measures		Utilisation measures				
	Waiting time	Riding time	System time	Lift response time	No. of waiting passengers in lobby (max.)	No. of lift users originating from a floor (max.)	Proportion of lift time (%)				No. of passengers in lift
							travelling	loading	unloading	idle	
Existing (non-zoning)	3:04	1:51	4:55	2:15	29.77 (G/F: 115.7)	292.39 (G/F: 552.23)	41.5	34.5	23.8	0.2	10.55

Based on the above results, a reasonable, compromised scenario (similar to Scenario 4) is suggested as follows: upper/lower floors zoning (with 9/F as a common floor); no B3 access for the two lifts of the higher-floors group; no up-peak feature being activated; and disabling "down" buttons for only a few high floors (in view of their heavy extreme-floor traffic). This scenario is preferred to the non-zoning scenario (Scenario 1) as the upper floor passengers (often the source of complaints) benefit from it and the average waiting time is not much longer.

5.2 Performance evaluation of hospital B

Hospital B consists of a 12-floor central block (a basement floor, B; G/F; 1/F – 10/F) served by four passenger lifts. It is situated next to a light railway station that brings in regular passengers. Preliminary field studies indicated that the peak period occurred in the late afternoon (16:30 – 18:30), and that the traffic demand was more than twice that of hospital A. After 11 days of data collection, it was observed that the up-trip traffic from G/F accounted for 48% of the total traffic loading, while the inter-floor traffic among non-terminal floors was much less significant than that of hospital A.

After discussion, a performance evaluation of the existing situation (non-zoning policy) was carried out. The lift control was similar to that of hospital A, and only one special lift feature, a full load bypass, was in use at the time of the study.

The results shown in Table 4 clearly indicate a higher level of congestion than was found in hospital A due to the significantly heavier demand in hospital B. Detailed results show that G/F is the most congested floor with up-trip passengers waiting an average of four minutes. The average waiting time experienced by passengers is over 35% longer than the average (first) lift response time. This implies that G/F passengers are often prevented from entering the first arriving lift. All lifts are busy most of the time with an overall average of about 11 passengers in each lift (a third of the full capacity).

In view of hospital B's heavy demand on lower floors and its middle-size building, the implementation of zoning may benefit lower floor passengers at the expense of higher floor passengers. Nevertheless, we suggested that activating up-peak and longest-wait lift features could bring some improvement. The hospital's management later adopted this suggestion. In addition to changing the technical lift features, the management imposed other monitoring control to regulate passenger traffic: visitors were restricted to passenger lifts; a waiting line arrangement was adopted to ensure a first-come-first-served queuing discipline; and a signpost displaying expected waiting times was put up before the waiting line. The lift performance was reported to have improved after such changes were implemented.

5.3 Performance prediction of hospital C

Hospital C is a yet-to-be-commissioned new hospital with a 10-floor building (a lower ground floor, LG; G/F; 1/F – 8/F) to be served by six passenger lifts. There will be six escalators running between LG and 1/F to divert some passenger traffic from the lifts. (Hospitals A and B have no escalator due to either resource or space constraints.)

Demand projection for hospital C is based on that of hospital A (see subsection 3.3), where a more detailed study was carried out. For ease of comparison with hospital A, the same peak duration of 100 minutes is simulated. The initial implementation is intended to be the non-zoning policy. Alternative zoning policies and the effect of traffic diversion to the escalators are tested for the scenarios given in Table 5.

Table 5

Proposed scenarios in hospital C for evaluation by the DSS

Scenario	Zoning policy	Traffic intensity	Special lift features
1a	Non-zoning	100% (from demand projection)	• full load bypass (80% capacity) • longest-wait (20 sec.) • up-peak (60% load from G/F => assign 2 lifts) • faster lift acceleration/ deceleration
1b	(Same as Scenario 1a)	50% of LG – 1/F internal traffic diverted to escalators	(Same as Scenario 1a)
1c	(Same as Scenario 1a)	100% of LG – 1/F internal traffic diverted to escalators	(Same as Scenario 1a)
2	Lower/upper floors zoning • Lifts 1-3: LG, G/F – 4/F • Lifts 4-6: LG, G/F, 4/F – 8/F	100%	(Same as Scenario 1a)
3	Even/odd floors zoning • Lifts 1-3: LG, G/F, 1, 3, 5, 7/F • Lifts 4-6: LG, G/F, 2, 4, 6, 8/F	100%	(Same as Scenario 1a)

To summarise the simulation results: the lift performance for hospital C is better than that for hospitals A and B as more lifts with faster mechanisms will be installed, and as the building has fewer floors. Passenger waiting time is close to the lift response time (as a result of the faster lifts). While the average waiting time for each scenario tested is low (less than 1 min. in all cases), zoning policies (Scenarios 2 and 3) have more than double the average amount of waiting time of their non-zoning counterparts (Scenarios 1a – 1c). A majority of passenger traffic is found at both the origin and destination among floors G/F – 4/F (39% of total traffic). Hence, any zoning policy that assigns fewer lifts to serve the lower floors leads to an overall deterioration in service. The up-peak and longest-wait features (with a 20-second limit) cause the lifts in the upper-floor group (Scenario 2) to move frequently between extremes, resulting in a poor service on upper floors and low utilisation for this lift group.

A reasonable scenario for hospital C could be as follows: increase the time limit of the longest-wait feature; deactivate any up-peak feature; and if a zoning policy is desired, assign a majority of lifts to serve LG – 4/F and reset the parking level to upper floors for lifts serving such floors.

The DSS is currently being applied to another hospital undergoing redevelopment and expansion. It is anticipated that an increase in Hong Kong's population will initiate the construction of more new hospitals or the renovation/expansion of existing hospitals. The proposed modelling approach and the DSS with its special lift features and general zoning policies are essential planning tools to be used in close co-operation with a hospital's management.

5 Conclusions

The successful development and implementation of the DSS tool, the HLS, has enabled the planners to evaluate various operational scenarios proposed directly by a hospital's management. The HLS has led to a better understanding of the relationship between the lift service experienced from the users' perspective and the data logged by the lift system. Under conditions of light to moderate traffic (as in hospital A and hospital C), the average passenger waiting time is close to or slightly less than the lift response time. As traffic becomes excessive (as in hospital B), the former time measure will have a larger mean and variance than the latter. This implies that the lift performance figures from the data logger cannot fully describe the passengers' experience. An interactive lift simulator allows all parties (the lift manufacturer, management, and users) to realise such discrepancies in advance and to design better policies. It further assists decision-makers in assessing funding requests from individual hospitals to install additional lifts.

Our work has focused on managing lift resources to provide a better service to meet traffic demand. However, the qualitative aspect (e.g., the control of demand to ensure discipline and fairness among passengers, and the provision of information about expected waiting times) should also be considered by management. In the case of hospital B, an improvement in its lift service was reported later.

A further contribution of our work is that it presents a new approach for lift traffic data collection and the modelling of inter-floor demand. The user-option of an integrated zoning policy has not been offered by any existing interactive lift simulator. It depends on a route-finding feature modified from the shortest path algorithm and allows better modelling of passenger behaviour in zoning design. As performance measures predicted by traffic calculations or given by the data logger cannot always act as substitutes for passenger experience, this route-finding feature should be incorporated in lift simulation systems. We predict that the need for visual interactive lift simulators with integrated zoning policies will increase with the rising demand for high-rise buildings and dynamic zoning policies. Some contemporary lift technology research has involved finding a good or near-optimal zoning policy under the detected traffic pattern (So and Chan, 1997). Our DSS, or the underlying methodology, could be used as a performance evaluator for any zoning policy due to its flexibility. Passenger characteristics not considered in existing lift simulators include the modelling of "blind" users. Regarding the lift features, apart from including the standard features of full load bypass, longest-wait, and up-peak, lift failures and the disabling of certain lift buttons on specified floors have been modelled.

The basis of traffic demand projection for a new hospital has been outlined and implemented. The process involves joint effort of the hospital's management with the planner using the DSS. In the forecasting procedure, we can incorporate traffic data from existing hospitals (offering a similar set of functions) and prescribed traffic data from the new hospital.

We have described its implementation in two existing hospitals and a yet-to-be-commissioned new hospital. A similar project is being developed for another hospital undergoing redevelopment and expansion.

Extensions of our work could include incorporating the special control feature of a disabled lift button(s) on specified floors as a user-option. This would force the lift on these floors to go in a certain direction, but will ensure the lift service remains available to all floors, especially during busy periods. Such a feature already exists in some buildings but is not mentioned in the current literature.

The techniques described in this paper can also be used in other general-purpose lift simulation systems as the passenger traffic groups and their characteristics will be simpler than those of the hospital traffic.

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Appendix A

The lift movement is described by the profile in Figure 11. To start off from some origin towards a destination of a given distance s_d metres away, the lift undertakes an initial acceleration a_0 (start-up acceleration). It is assumed that the acceleration then increases *linearly* until it reaches the maximum acceleration a_{max} at time t_0 (the start-up time). Thereafter, this acceleration will remain constant and hence the speed will increase linearly. If the destination is far away enough (*Case 1*), the speed will reach a maximum of v_{max} (the maximum speed), after which the speed will remain constant for some time. Irrespective of whether the maximum speed v_{max} is attained, at a certain point in time, the lift will decelerate to zero speed in a symmetric profile in the same way as it starts off from zero speed. (See Figure 11.)

The following time function is used to find the nearest lift to be dispatched to a specified floor s metres from the origin. When a lift is starting up or decelerating, it cannot change its motion. The time taken to cover such a short distance s is set to infinity so that the lift will not be chosen.

[Insert Figure 11: Lift profiles (acceleration, speed, and distance)]

Let $a(t)$, $v(t)$, and $s(t)$ denote the acceleration, speed, and distance covered at time t, respectively. The break points v_0 and t_c (in Figure 11) are obtained by calculus:

$$\begin{aligned}
v_0 &= v(t_0) \\
&= \int_0^{t_0} a(t)dt \\
&= \int_0^{t_0} \left[a_0 + \frac{(a_{\max} - a_0)}{t_0} \cdot t \right] dt \quad \text{(assumption of linear increase in acceleration)} \\
&= (a_{\max} + a_0) \cdot t_0 / 2 \\
t_c &= t_0 + (\text{time to reach speed } v_{\max} \text{ from } v_0 \text{ with acceleration } a_{\max}) \\
&= t_0 + (v_{\max} - v_0)/a_{\max} \qquad \text{(A1)}
\end{aligned}$$

Proof (*Case 1*: lift reaching maximum speed v_{max}**).** The time function $t(s)$ is derived by finding the inverse of the distance function $s(t)$ for different segments of the curve in Figure 11.

$0 \le t \le t_0$:

$$s(t) = \int_0^t \left[\int_0^y a(x) dx \right] dy$$
$$= \int_0^t \left[\int_0^y a_0 + \frac{(a_{\max} - a_0)}{t_0} \cdot x \;\; dx \right] dy$$
$$= (3a_0 + \frac{t}{t_0}(a_{\max} - a_0)) \cdot t^2 \Big/ 6$$

At break point t_0,

$$s(t_0) = (a_{\max} + 2a_0) \cdot t_0^2 \big/ 6$$
$$\equiv s_0 \qquad \text{(A2)}$$

The time function for $0 < s < s_0$ is set to infinity as the lift is starting up.

$t_0 \le t \le t_c$:

$$s(t) = s_0 + \int_{t_0}^{t} v(x)\, dx$$
$$= s_0 + \int_{t_0}^{t} v_0 + \mathrm{a}_{\max} \cdot (x - t_0) \;\; dx$$
$$= t^2 \cdot (a_{\max}/2) - t \cdot (a_{\max} - a_0) \cdot t_0 / 2 + (a_{\max} - a_0) \cdot t_0^2 \big/ 6 \qquad \text{(A3)}$$

At break point t_c,

$$s(t_c) = t_c^2 \cdot (a_{\max}/2) - t_c \cdot (a_{\max} - a_0) \cdot t_0 / 2 + (a_{\max} - a_0) \cdot t_0^2 \big/ 6$$
$$= \left[(a_{\max} - a_0)(a_{\max} + 3a_0) \cdot t_0^2 + 12 v_{\max}^2 \right] \Big/ (24 a_{\max})$$
$$\equiv s_c \qquad \text{(A4)}$$

The time function for $s_0 \le s \le s_c$ is given by the inverse of $s(t)$ for this interval:

$$t(s) = \left[3(a_{\max} - a_0) \cdot t_0 + \sqrt{72 a_{\max} \cdot s - 3(a_{\max} + 3a_0)(a_{\max} - a_0) \cdot t_0^2} \right] \Big/ (6 a_{\max}) \qquad s_0 < s \le s_c \qquad \text{(A5)}$$

$t = t(s_d)$:

At time t_c, the lift will attain the maximum speed v_{max} for some time before decelerating. By symmetry of the distance profile, the distance s_d to the destination is obtained by:

$$s_d = 2s_c + v_{\max} \cdot (t(s_d) - 2t_c)$$

Hence, $$t(s_d) = 2t_c + (s_d - 2s_c) / v_{\max} \qquad \text{(A6)}$$

$t_c < t \le t(s_d) - t_c$:

By symmetry, the lift attains speed v_{max} during this time interval. Hence,

$s(t) = s_c + v_{max} \cdot (t - t_c)$

=> $t(s) = t_c + (s - s_c) / v_{max}$ $\qquad s_c < s \le s_d - s_c$ (A7)

$t(s_d) - t_c < t < t(s_d)$:

The time taken to cover segment $[0, s]$ ($0 \le s \le s_c$) is the same as for segment $[s, s_d]$ ($s_d - s_c < s \le s_d$). Hence,

$$t(s) = t(s_d) - t(s_d - s) \qquad s_d - s_c < s \le s_d - s_0 \qquad \text{(A8)}$$

$$t(s) = \infty \qquad s_d - s_0 < s < s_d \qquad \text{(A9)}$$

Proof (*Case 2*: lift not reaching maximum speed v_{max}**).** This proof is identical to the proof for *Case 1*, except that the destination (s_d metres from the origin) is not far away enough for the maximum speed v_{max} to be attained (i.e., $s_d < 2\ s_c$). Hence, the time function for segment $s_c < s \le s_d - s_c$ in (A7) of *Case 1* does not exist here. The point of symmetry occurs at $s = 0.5s_d$. This replaces the limit point s_c in (A4) and (A7). Finally, $t(s_d)$, the time taken to reach the destination, is, by symmetry, twice that of $t(0.5s_d)$.

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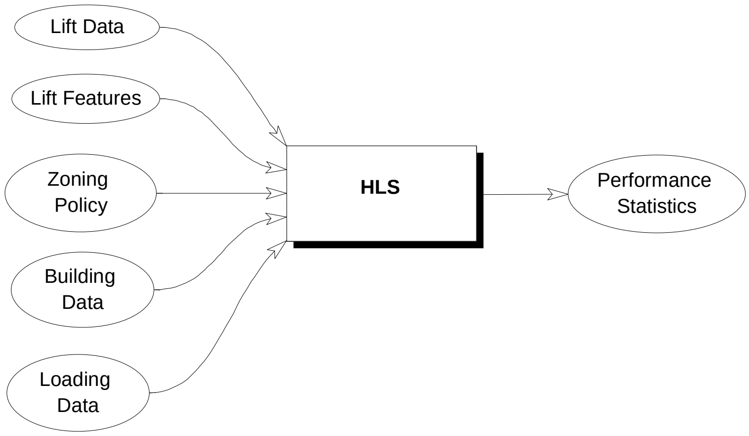


Figure 1. Hospital lift simulator (HLS)

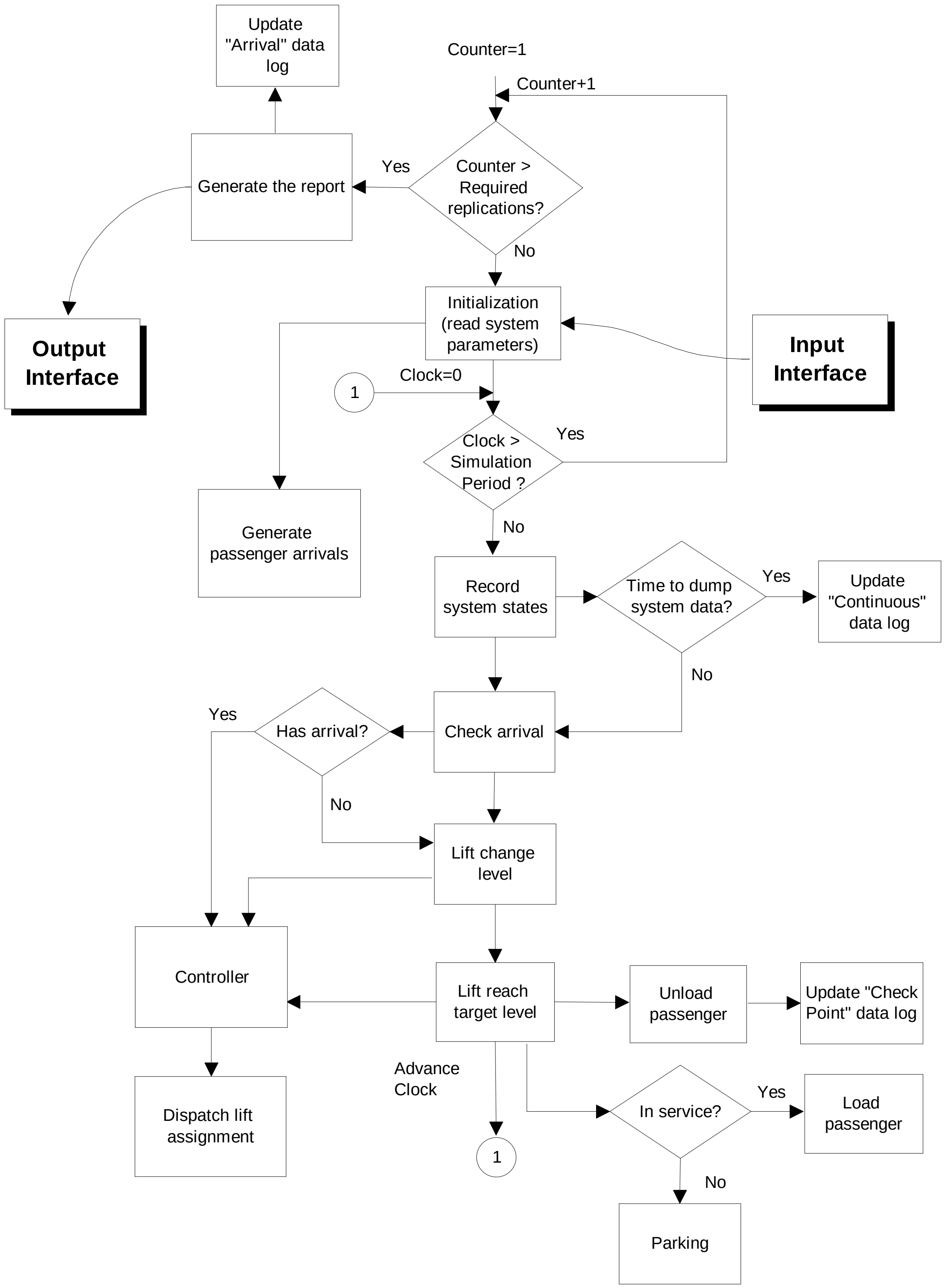


Figure 2. Algorithm of the HLS

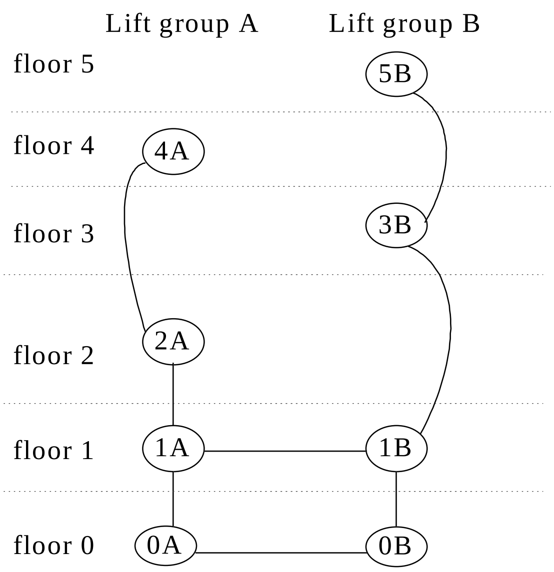


Figure 3. The zoning policy's network for finding the changeover floor(s) and lift group(s) by Dijsktra's algorithm

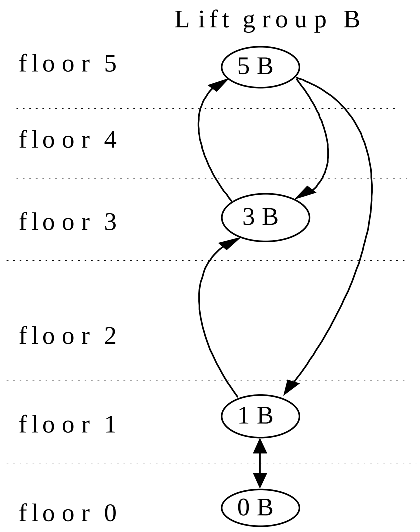


Figure 4. The zoning policy's network of disabled "down" button on floor 3

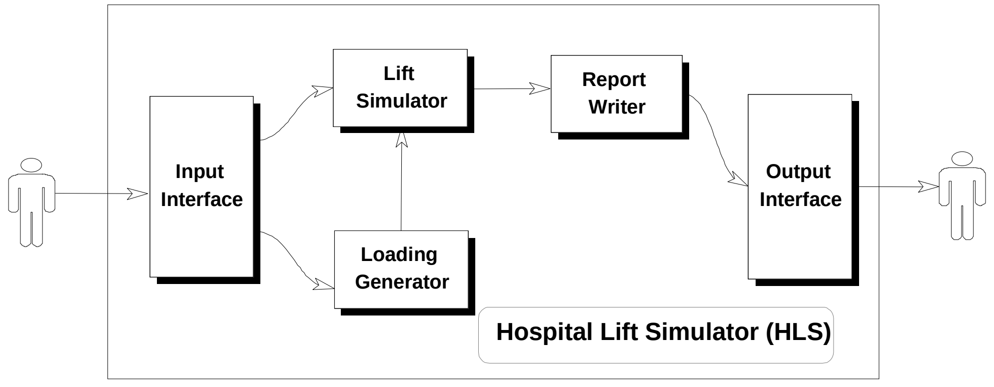


Figure 5. Simulation software

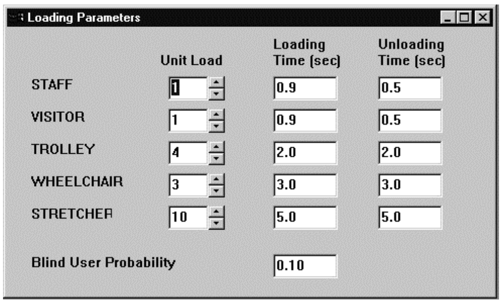
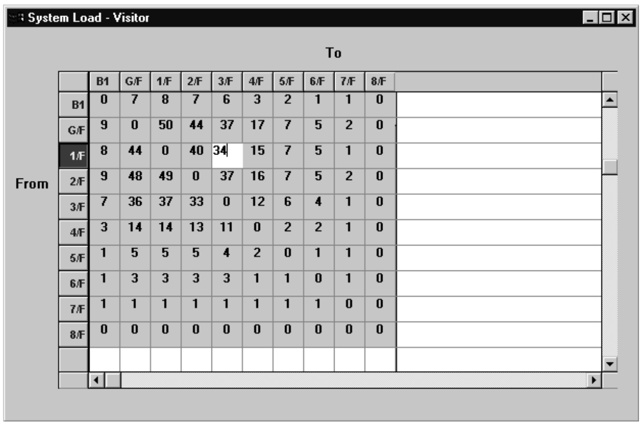


Figure 6. Loading data – parameters



	B1	G/F	1/F	2/F	3/F	4/F	5/F	6/F	7/F	8/F
B1	0	7	8	7	6	3	2	1	1	0
G/F	9	0	50	44	37	17	7	5	2	0
1/F	8	44	0	40	34	15	7	5	1	0
2/F	9	48	49	0	37	16	7	5	2	0
3/F	7	36	37	33	0	12	6	4	1	0
4/F	3	14	14	13	11	0	2	2	1	0
5/F	1	5	5	5	4	2	0	1	1	0
6/F	1	3	3	3	3	1	1	0	1	0
7/F	1	1	1	1	1	1	1	1	0	0
8/F	0	0	0	0	0	0	0	0	0	0

Figure 7. Loading data – inter-floor traffic (visitors)

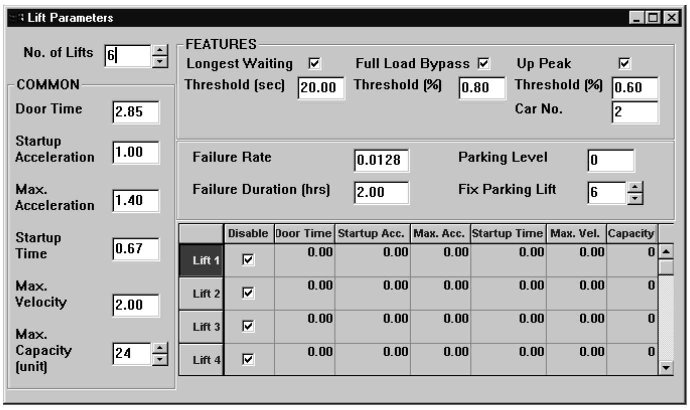


Figure 8. Lift data and features

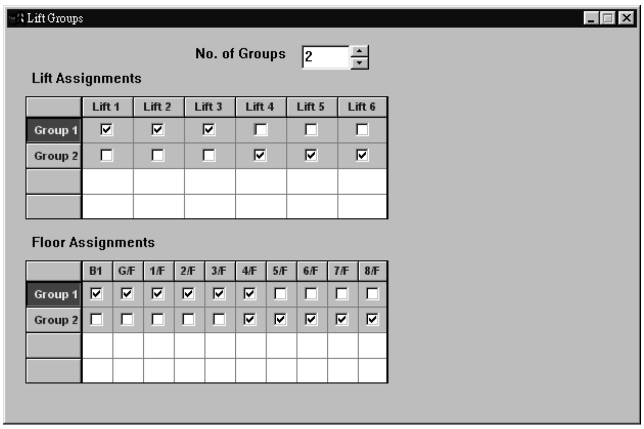


Figure 9. Zoning policy

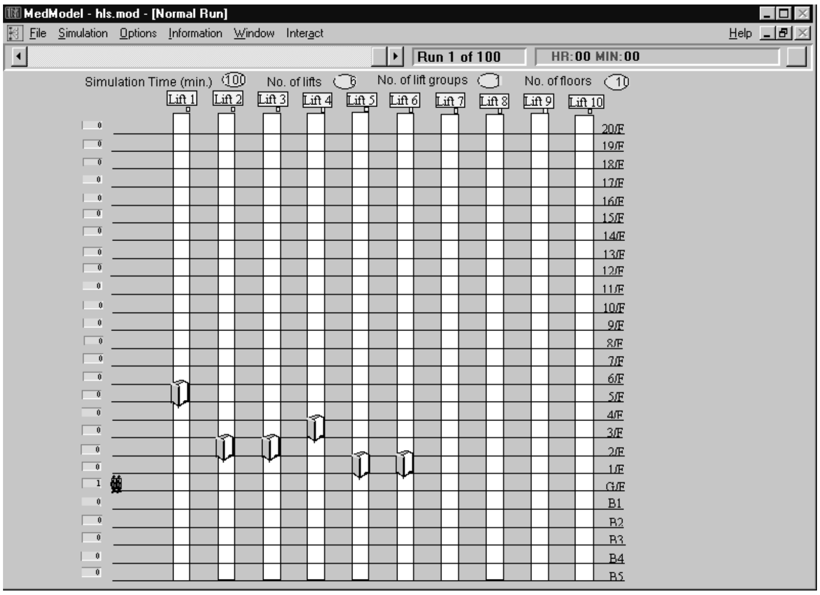


Figure 10. Animated display of a simulation run

Case 1:

(maximum speed v_{max} would be attained,

or equivalently, $s_d \geq 2\, s_c$)

Case 2:

(maximum speed v_{max} would not be attained,

or equivalently, $s_d < 2\, s_c$)

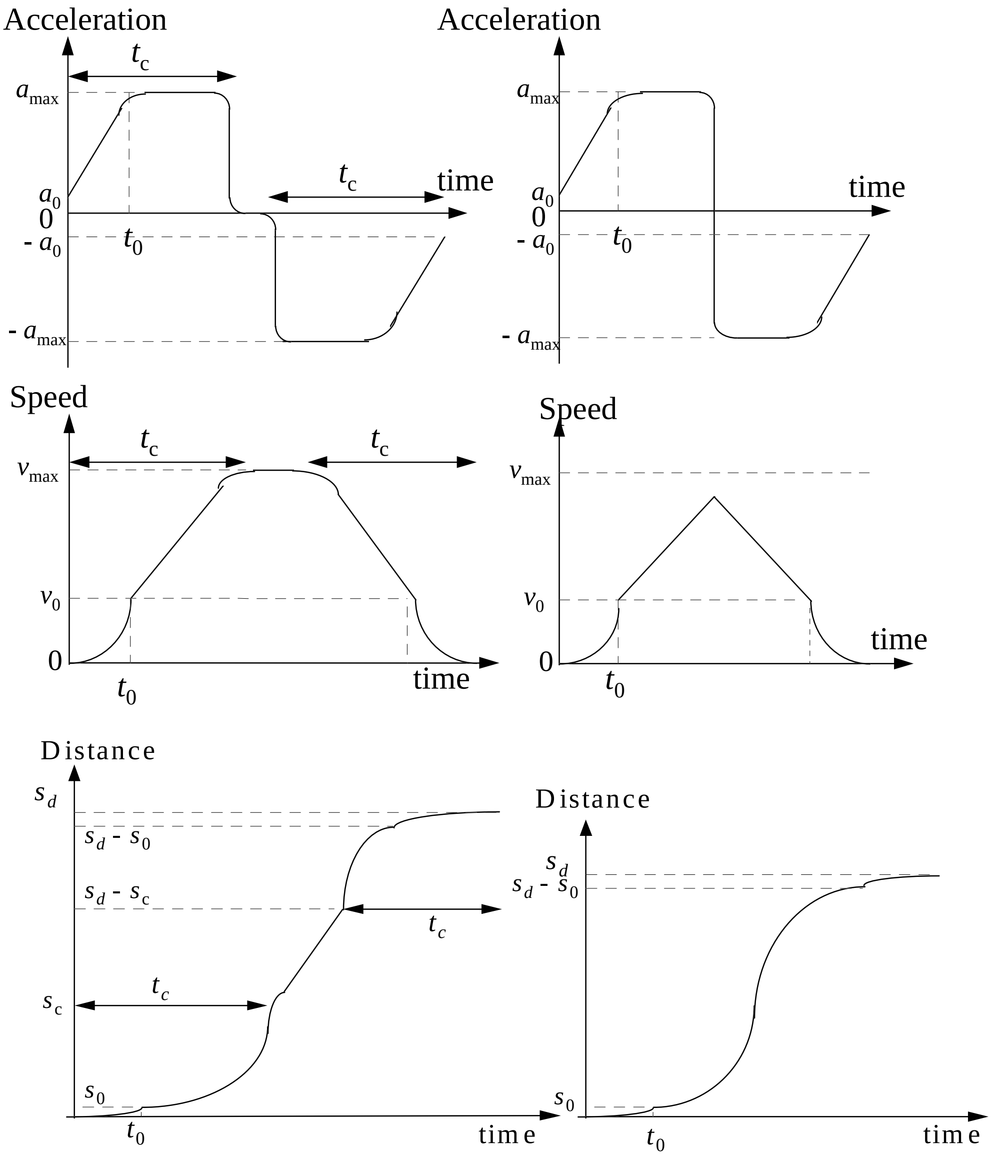


Figure 11. Lift profiles (acceleration, speed, and distance)