Planning and Control Models for Elevators in High-Rise Buildings

Marja-Liisa Siikonen

KONE Corporation
P.O. Box 8
SF-00331 Helsinki, Finland

Helsinki University of Technology
Systems Analysis Laboratory
Research Reports
A68

October 1997

ABSTRACT

The passenger service level in an elevator system depends on the planning of the elevator group and on the control of the elevators. In this thesis the contribution of passenger and elevator traffic for an elevator group with multiple shafts is studied by simulations and theoretical analysis.

During this work an elevator control system, the Traffic Master System 9000 (TMS9000), was developed. The TMS9000 group control system optimizes passenger waiting times instead of hall call times, and the control actions can be started in advance, which is not the case with conventional controls. With the TMS9000 control system, average passenger waiting times became shorter and more balanced floor by floor compared to conventional controls. The functional properties of the TMS9000 group control system were tested with the Advanced Lift Traffic Simulator (ALTS), which is described in the thesis. ALTS has also been applied in elevator planning to predict hall call times in new buildings, or to estimate improvement potential in hall call times for existing elevator groups. Simulation has revealed new correlation between the passenger and elevator traffic. In this thesis, new equations and planning criteria for the mean passenger journey time and ride time inside the car during an up-peak are introduced, and the results are verified with simulations.

Keywords: elevator planning, group control, call allocation, simulation, optimization, fuzzy logic, forecast

PREFACE

This thesis is based on work that was carried out in the KONE Research an Development Department and, later, in the KONE Elevators Research Center. My starting point was to develop an elevator traffic simulator, and to get acquainted with the elevator planning problems. I am very grateful to Mr. Nils-Robert Roschier, and also to the late Mr. Matti Kaakinen, for their encouragement and enthusiasm shown towards my work. Later on the work continue with the development of group control principles. I owe my thanks to Mr. Risto Kontturi, who also gave me the opportunity to finish this thesis. I also want to express my gratitude to my supervisor, Prof. Raimo Hämäläinen, for his interest in my work.

The group control study included in this thesis started in 1985 as a research project funded by the Technology Development Centre in Finland (TEKES). The objective was to apply an expert system framework for embedded applications. One of the applications in this project was the elevator group control, where co-operation was made with Helsinki University of Technology (HUT). The original idea of the work was subsequently rejected, but the study formed the basis of the new group control for high-rise buildings, the KONE Traffic Master System (TMS) 9000. The TMS9000 group control with artificial intelligence was specified and partly managed by the author. A number of people took part in the TMS9000 control development project. I want to thank all the people who participated in the TMS9000 development for the innovative and creative atmosphere. I owe special thanks to Mr. Jussi Leppälä, who finished his master of science thesis during the TMS9000 development. His work dealt with the passenger traffic forecasts, which have greatly assisted in adding the passenger insight to the elevator control.

During the work in the Elevators Research Center, mathematical studies were made together with the Technical Research Centre of Finland (VTT). I want to thank Dr. Jorma Virtamo and Mr. Samuli Aalto, who clarified various elevator traffic problems during the co-operation. Among the results was a new control with future event simulation, which also provided a basis for the development of the DACA control described in this thesis.

LIST OF PUBLICATIONS

I Siikonen, M-L. Simulation - a tool for enhanced elevator bank design. Elevator World, 1991. No. 4, pp. 30-37.

II Siikonen, M-L. Elevator traffic simulation. Simulation, 1993. Vol. 61, No. 4, pp. 257-267.

III Siikonen, M-L. Customer service in an elevator system during up-peak. Transportation Research, 1997. Vol. 31B, No. 2, pp. 127-139.

IV Siikonen, M-L. Control methods for an elevator group, Proceedings of the Nordic Operations Research Conference, NOAS '93. Trondheim, Norway, 1993.

V Siikonen, M-L. Elevator group control with artificial intelligence, Helsinki University of Technology, Systems Analysis Laboratory, Research Reports A67, May 1997. 32 p. ISBN 951-22-3588-9.

VI Siikonen, M-L., Leppälä, J. Elevator traffic pattern recognition. Proceedings of the Fourth World Congress of the International Fuzzy Systems Association, Brussels, Belgium, 1991. pp. 195-198.

VII Siikonen, M-L., Kaakinen, M. TMS9000 group control - using artificial intelligence to improve passenger service quality. Elevator Technology 5, Stockport, England: IAEE Publications, 1993. pp. 238-246. ISBN 0-9513498-6-4.

Republished in Elevatori, 1994. Vol. 23, No. 3-4, pp. 25-36. and

in Lift Report, 1994. Vol. 20, No. 3-4, pp. 32-41.

This thesis is based on a collection of seven publications. Publications I and II deal with the elevator traffic simulator, ALTS, which was developed by the author. ALTS belongs to the integrated elevator planning tools in KONE. In Publication III a new equation for the passenger journey time is introduced. With ALTS different landing call allocation principles have been studied, and some of the author's results are shown in Publication IV. The three remaining articles deal with the TMS9000 group control system. Publication V is the most comprehensive description of the TMS9000 control and it was published last. The last two articles partly overlap with Publication V and are not as detailed since they are conference presentations. Publication VI is a short description of the utilization of the fuzzy logic in the TMS9000. It is based on Mr. Jussi Leppälä's master of science thesis that was led by the author. Publication VII is a general description of the implementation of the TMS9000 control system. It was written by the author and by Mr. Matti Kaakinen, and it was presented at the IAEE's (International Association of Elevator Engineers) Fifth Conference on Elevator Technologies. The article won the best paper award in the conference, and was later reprinted in two elevator magazines.

The introduction part of this thesis describes how the passenger insight is brought into elevator control and planning. The exact methods and equations are presented in the publications, and they are only briefly reviewed in the introduction.

1. INTRODUCTION

Elevators have been built throughout history but the first modern passenger elevators were developed no more than about 150 years ago. Steam and hydraulic elevators had already been introduced by 1852, when Elisha Otis made one of the most important elevator inventions, the clutch, which prevented the elevator from falling. Following this, in 1857, the first passenger elevator was installed in the store of E. Haughwout&Company, New York. The development of elevator technology was fast. With the advent of modern high-rise buildings, more elevator history than in any other single location was made in 1889, when the 321-meter-high Eiffel Tower was built for the Universal Exposition in Paris. In the Eiffel Tower, hydraulic double-deck elevators operated between ground level and the second platform. Between the second and third platforms two cars counterbalancing each other handled the traffic. The early hydraulic and steam-driven elevators functioned with pressurized water, which was either taken from the city water pipes or provided by steam engines. The elevator car was connected to a long piston that moved up when water was pumped into a cylinder, and came down when water was released by a hydraulic valve. In 1880 Werner von Siemens introduced the utilization of electric power. Soon after, the *geared or gearless traction electric* elevators started to replace the hydraulic elevators. The development of electric elevators added impetus to high-rise construction. The fastest elevators today move at about 10 meters per second.

In Finland, elevators were first distributed by Strömberg. The KONE corporation was registered in 1910. In 1918 it started to design its own elevators, and the first four KONE elevators were delivered later that year. The first geared traction elevators from KONE were delivered to the Stockmann department store in 1928. KONE started to design its own AC and DC motors, and in the 1930's almost all the elevator components were being produced in-house. In electric elevators, the machinery for driving the elevator is usually located directly above the elevator hoistway in a machine room. After the middle of this century, hydraulic and ram elevators made a come-back, since it was cheaper to place the machine room at the bottom of the building (Virkkala 1983). Modern hydraulic elevators function with oil, which is pumped by electric power. Since the speed of hydraulic elevators is low, they became popular especially in residential buildings, and in installations where heavy loads are transported. A recent innovation that requires no oil is a new hoisting unit where a synchronous axial motor is installed in the elevator shaft (Hakala 1995). With this concept the control boards are situated at the highest landing floor and no separate machine room is required.

In a single elevator system the *elevator control* handles all the equipment. In the case of several elevators where each elevator is in its own shaft, the transportation capacity can be increased by a common *group control* that delivers the hall calls to the elevators. The first electrical controls were realized by relay techniques, the same kind of relays that were used in telephone exchanges. In the 1970's the principles of relay equipment were applied to electronic controls. In KONE, the first completely microprocessor-based control system was developed in the beginning of the 1980's,and it was first tested with a hybrid traffic simulator. With microprocessors, mathematical methods and sophisticated call allocation algorithms are used to optimize hall calls to the elevators. The rapid development of processor technology has made it possible to distribute the "intelligence" from the machine room to the elevator components, even to the hall call buttons. In a modern group control, a huge amount of information is handled during the hall call allocation compared to the old relay controls. The first aim of this work is to describe new microprocessor-based *hall call optimization methods* that optimize passenger service level.

The other aim of the present work is to bring the passenger point of view to elevator planning. A basis for the passenger service level is already set when configuring the elevator groups. Sufficient transportation capacity and good elevator service for the varying traffic situations during the day have to be guaranteed when selecting elevators for a new building. A single elevator with passengers arriving randomly at the main entrance floor has been modeled with bulk service queuing theory (Bailey, N. T. J., 1954; Aalto, S., 1995). The average waiting times and queue lengths for a multi-car elevator system have been modelled with multi-bulk service queuing theory for the up-peak traffic (Alexandris, N. A., 1979). The up-peak situation, where passengers arrive at one entrance floor, i.e. at the lobby, and travel to the upper floors, is the most demanding for the elevator transportation capacity. In an up-peak situation the average time it takes for an elevator to serve the car calls and return back to the lobby, i.e. *round trip time*, is calculated using probability theory. In conventional elevator planning the up-peak handling capacity and interval are calculated from the round trip time value. The elevator group is chosen using standardized *handling capacity* and *interval* values for different types of buildings. In a real building, passengers arrive at several floors at the same time. Then the group control has a great effect on the passenger service times. The impact of the group control decisions on the passenger service times in different traffic situations cannot be calculated analytically. Passenger service times and elevator performance can be determined by simulating the contribution between passenger traffic flow and the elevator performance.

In the following, elevator group control principles, traffic simulation and elevator planning are reviewed. Several fields of mathematics are applied, such as statistical methods, optimization, simulation and queuing theory. The basic terms are defined in Section 2. A review of group control principles is given in Section 3. Passenger waiting time optimization by the TMS9000 control system is described in Publication V. The measurement and forecasting of passenger traffic flow in a building, and the traffic pattern recognition using fuzzy logic is explained in Publications VI and VII New aspects in hall call allocation are presented in this section and in Publication IV. The function of group controls for different traffic patterns is tested with simulations. The ALTS simulator is described in Publications I and II. Methods for generating theoretical passenger traffic patterns or for reconstructing the real passenger traffic flow from measured elevator traffic events are explained in Section 4. Simulation is used also as a tool when planning elevator installations. General elevator planning principles are described in Section 5. New equations for the mean passenger ride and journey time are derived in Publication III and they are compared with the known approximations for elevator planning parameters. Finally, the results of the publications are summarized and a glance is taken at future developments.

2. MAIN DEFINITIONS

Passengers arrive at an elevator system randomly and they are served in batches. The actual passenger arrival rates in a building can be assumed to follow the Poisson distribution (Alexandris 1977). When a passenger arrives at a landing floor and gives a hall call, the group control allocates the call to the most suitable elevator. The time a hall call(landing call) stays on is called a *hall call time*. When a selected elevator starts to decelerate to the call floor, the hall call is cancelled. The *system response time* (Barney 1995) and *call waiting time* (Fujino et al.1992) resemble the definition of the hall call time. Those times are measured from the moment of hall call registration until the car arrives to the floor and starts opening its doors. *The passenger waiting time* starts when a passenger arrives at a landing floor, and ends when he enters the elevator. The *passenger ride time* starts when a passenger enters a car and gives a car call (destination call), and ends when he exits the car at the destination floor. The total time a passenger spends within an elevator system first by waiting and then by riding inside a car is called the *journey time*, also called the service time (Powell 1992) and the *time to destination* (NEII 1994). Journey time is approximated by *average time to destination* (Fortune 1995), transit time to destination (Schröder 1984), or by *maximum passenger transit time* to the destination (Strakosch 1984). The travel time from the bottom to top floor at full speed is used to define the elevator speed. In elevator planning, a theoretical up-peak situation where all the elevators leave the lobby with 80 per-cent load is normally used. The two most important planning parameters, the up-peak interval and handling capacity, are calculated from the round trip time. The *round trip time* starts when a car opens its doors at the lobby, and continues until an elevator has made a trip around the building and starts to open its doors after returning to the lobby. The *interval* is the average time between car departures from the lobby. The *handling capacity* gives the number of passengers the elevator system can transport in five minutes during up-peak. The main parameters in defining the passenger service level used in this work are shown in Figure 1.

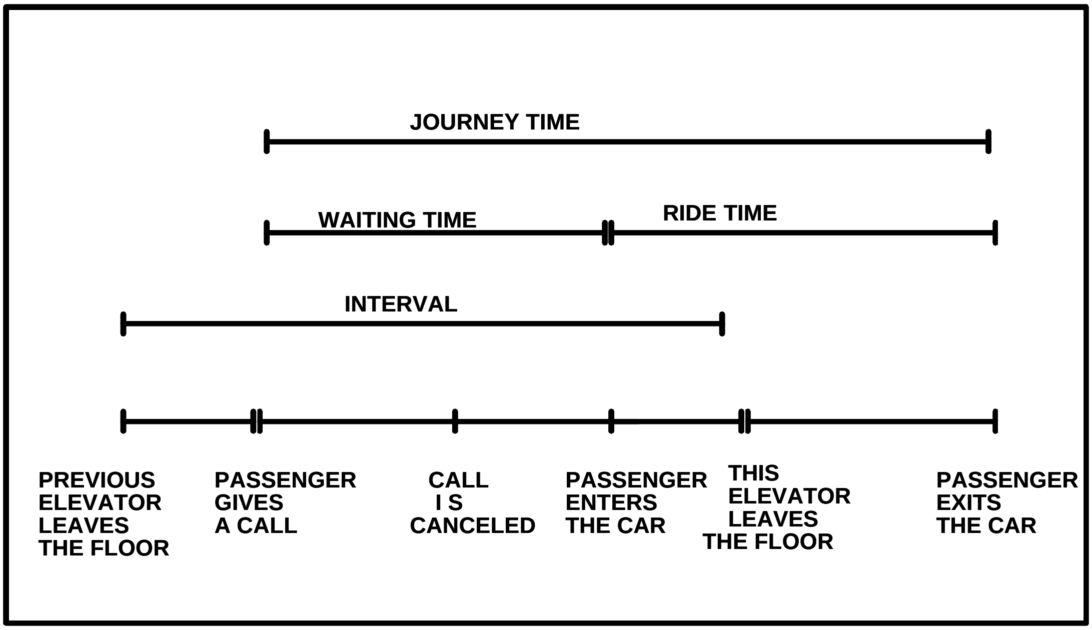


Figure 1. The interval and the passenger service level parameters. In the graph, one passenger per hall call is assumed.

3. OPTIMIZATION BY GROUP CONTROL

3.1 Architecture of an elevator control system

A typical architecture of an elevator control system is shown in Figure 2. The control boards of an elevator group are usually situated in a machine room. The group control is the "brain" of the elevator system, deciding where the cars should go and stop. There can be one or several group controls in an elevator group. One of the group controls is the master that delivers the hall calls to the elevators, and the other group controls are backups. Other functions inside the car, e.g. registering and canceling of car calls, door control, and measurement of the car load, are handled by the elevator control. Using the latest microprocessor technology, part of the elevator control has been distributed among the elevator components. "Intelligent" elevator components communicate with each other through serial transmission using Control Area Network (CAN). Modern elevator controls provide built-in elevator monitoring devices (Chapman 1994) or remote building monitoring systems (Kawano et al.1994) to follow the elevator traffic. Typical control software for an elevator component includes an operating system, task-scheduling programs, input, output and communication programs, and programs for controlling and optimizing the function of the component.

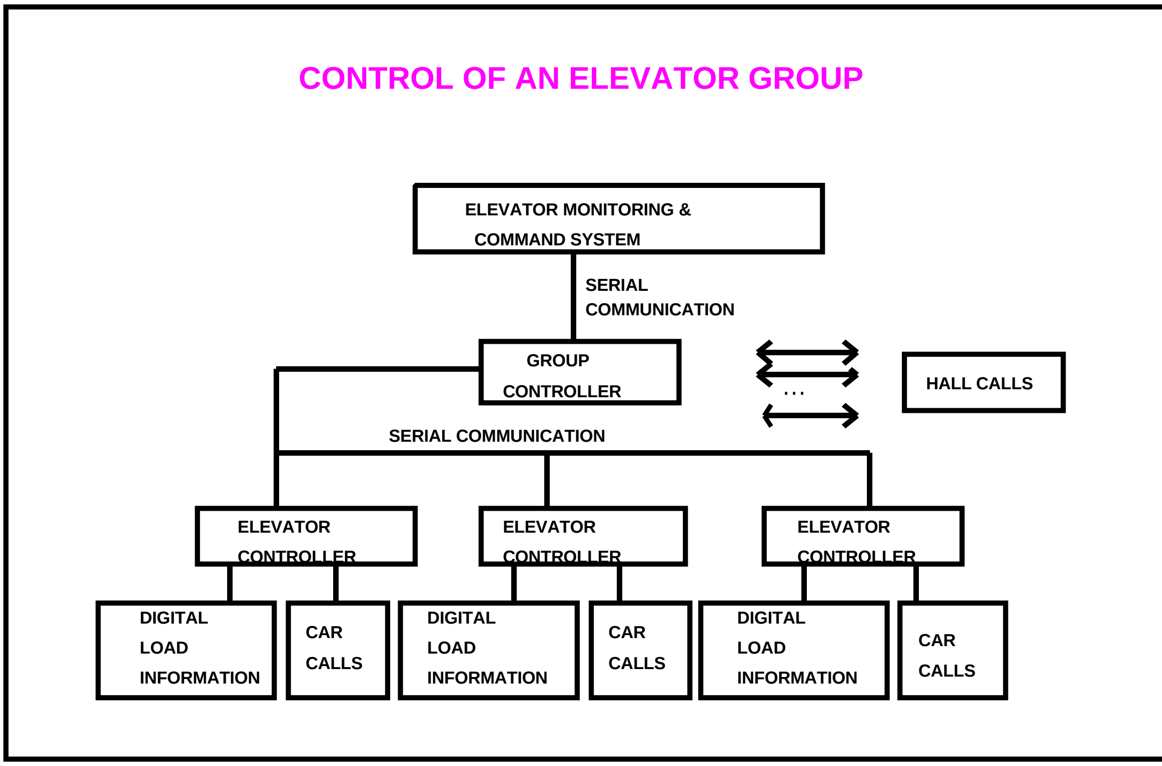


Figure 2. The architecture of an elevator control system.

The group control allocates hall calls to the most suitable elevators by optimizing the cost function. The most usual optimization target in an elevator control is to minimize hall call times. It was, however, found that by optimizing passenger journey times the number of elevator stops is reduced, which increases the handling capacity (Barney et al.1985;Closs 1970). The same traffic can be handled with fewer elevators compared to a conventional system. In the M10 control system (Schröder 1990) special keypads at the landing floors are used. Passengers can dial their destinations already at the landing floors and no car calls inside the elevators are needed. With normal up- and -down hall call buttons, passenger arrival floors, times, and destination floors cannot be determined, but they can be forecast. In the TMS9000 control system the passenger traffic flow is forecast and the passenger waiting times are optimized. In this section, the background of the group control principles is given first. The TMS9000 control system is only briefly described since it is characterized in more detail in Publications V, VI and VII. The cost function in multiple target optimization is discussed and new routing methods in the call allocation algorithm are described (Publication IV).

3.2 Group control principles

The first elevators were operated by simple mechanical devices, such as *"hand-rope" control* (Strakosch 1967). A passenger could call an elevator by operating a rope on both sides of the car. Since the shafts were not fully closed, the operation of elevators was quite unsafe. A primitive form of elevator control in a single car was based on an *attendant-operated* electrical car switch (Barney et al.1985). Using the switch, the attendant could manually drive the car up or down and decide at which floors to stop. The elevator efficiency and safety were increased with signaling devices at landings.

Push-buttons were introduced in the 1920's to give the attendant information on the traffic demand, and the elevator shafts became closed. If no memory for the hall calls is provided, the calls are handled with a *push-button control*. With the *non-collective controls* the traffic demand is handled by serving each hall call at a time. A new hall call can be registered after the service of the previous call is completed. This control principle is used in freight elevators. When the registered calls are memorised, the elevator can pick several hall calls during the up or down trip. If there is only one call button at each floor, the calls can be arranged in a time queue according to the order they have been registered, or they can be served collectively. In the *Interconnected Queue Selective* (IQS) control system the hall calls are picked one at a time from the time queue so that the oldest call is served first (Virkkala 1983). This type of control is used, for instance, in hospitals, where the bed calls are served one at a time. In collective control the car stops in floor sequence at each hall call. The *Interconnected Down Collective*(IDC) control system is often used in buildings where the traffic is mostly two-way between the ground level and the upper floors. This kind of traffic occurs, for example, in residential buildings. The elevator collects the hall calls during the down trip, i.e. serves the calls in sequence, stopping always at the nearest call floor. The IQS and IDC controls can be used by one car only or they can be applied for a group of elevators.

After automatic doors were developed in the 1950's, the traffic demand could be handled without attendants. In tall buildings, hall call buttons for both up and down directions were adapted. The most common call allocation principle, especially in the old relay controls, is the Interconnected Full Collective (IFC) control system. With two buttons at each floor, an elevator can pick the nearest hall call in front of the car in its direction of travel. The car calls given inside the elevator are always served in sequential order. After serving all the calls in the travel direction, the car moves to the furthest hall call in the opposite direction, where it reverses its direction. The efficiency of an elevator group was improved with a common central logic, the group control. The hall calls could be shared between several elevators where a common hall call button exists at every floor. The *group control* chooses the best elevator from a group of elevator cars to serve a given hall call. Group control dispatches cars to floors also for other reasons than hall calls, such as for parking, or if more than one elevator is needed at a busy floor. Elevators can be disconnected from the group for special service modes, such as emergency service, fireman's service or director/VIP service. A disconnected elevator operates independently of the other elevators.

One drawback of the collective control principle is the *bunching* of elevators. During heavy traffic there are a lot of hall calls to serve and the elevators have a tendency to move side by side, i.e. they start to bunch. This happens because elevators always stop at the nearest call and by-pass hall calls only when fully loaded. One of the early methods of preventing the bunching of elevators was to dispatch cars from the lobby *at proper time intervals*. A bus-type schedule for the elevators was applied. Elevators were delayed at the lobby for a certain time before they were sent to the upper floors. By delaying elevators at the lobby, part of the handling capacity was lost. In the 1970's collective control was first adapted to electronic controls. With electronic controls, however, collective controls were improved by giving *priorities* for the long or timed-out hall calls. Hall calls that had been on for a short time, were bypassed to get faster service for the timed-out calls. To some extent the elevators were kept apart from each other with this control. Peak traffic situations were handled with separate operation modes. In up-peak operation modes, such as next car up(Barney et al.1985), dispatching intervals(Bittar 1981), zoning of floors, and later a channeling option (Powell 1992) were used.

The allocation principles of relay and electronic controls were brought to the microprocessor controls at the beginning of the 1980's. Hall calls were still prioritized according to the call service times. A slight but fundamental change was made in the philosophy. It was no longer expected that hall call times would become long before the "timed out" hall calls were given better service. The hall call times were forecast with mathematical calculations. When it was found that a hall call would become long with the normal service order, a car would bypass some hall calls to provide faster service to this call before it became long. When bypassing other hall calls, it was checked that the bypassed calls could be served by other cars within an acceptable time frame. On some occasions bonuses and penalties were used. For example, a bonus was given to an elevator with a car call coinciding with the hall call when estimating the service time to the hall call. On the other hand, a penalty was given to some elevators, such as parked cars, when choosing the best car to serve a hall call.

One important feature in the modern *group supervisory controls* is the time when hall calls are finally reserved to the cars. The reservation moment can be seen in the signalization at the landing call floor. As soon as the hall call is finally designated to a car, an arrow above the car-door opening is illuminated. Simultaneously an audible gong signal is given to inform the passenger which car is going to serve the given hall call. The final reservation must be stable not to mislead the passenger. To get the best optimization result, the reservation is often made at the latest possible moment, i.e. when the elevator starts to decelerate to the hall call floor. The other extreme is to reserve hall calls finally to an elevator immediately the hall call is given (Hirasawa et al.1978). This shortens the psychological waiting time of the passengers. Passengers have more time to gather around the arriving elevator, which shortens the loading time. When the hall calls are allocated at an early stage, the future traffic events change the situation so that the early reservations are not as optimal as if the allocation was made at a later instant.

In the course of the fast development of microprocessor technology, the call allocation algorithms have become more sophisticated. Mathematical methods are applied in the elevator controls. The traffic in the building is measured and learned in statistical forecasts. Statistical forecasts are used when allocating new hall calls to the cars (Sakai et al.1984). Statistical traffic forecasts are also adapted to the controls with a late hall call reservation (Kameli 1989), even though the allocation principle is not critical to the future traffic events. The methods that learn and adapt to the traffic of a building, and use rules based on expertise are connected *to artificial intelligence* in the elevator technology (Aoki et al.1990). The uncertainties in the predictions and control actions are described by fuzzy rules (Umeda et al.1989; Powell et al. 1993). Neural networks can make the elevator controls completely autonomous so that the control parameters are tuned by the traffic of the building. Then the significance of pre-defined expert rules diminishes (Nakai et al. 1995).

3.3 Passenger waiting time optimization by the TMS9000 control system

The main idea of the Traffic Master System 9000(TMS9000) was how to optimize passenger waiting times, not only hall call times(Publication V). Artificial intelligence is used to learn the passenger traffic flow in the building. The call allocation algorithm uses the measured passenger traffic flow information to optimize passenger waiting times. All the existing hall calls are allocated continuously. According to the *Enhanced Spacing Principle*(ESP) the allocation starts from the call where there are most passengers waiting with a long predicted waiting time. Those calls are served first and long waiting times are cut. Average waiting times are balanced floor by floor, especially in buildings with uneven passenger arrival rates at different floors and directions. Fuzzy logic is utilized to recognize the prevailing traffic pattern. Altogether 26 different traffic patterns can be recognized using 36 fuzzy rules. The best matching traffic pattern for each time of day is searched according to the forecast traffic data. The group control activates special control actions during the peak traffic patterns, or during light traffic, in advance compared to conventional controls.

The statistical forecasts include information of entering and exiting passengers per floor and direction at fifteen minute intervals. The three traffic components, i.e. *incoming, outgoing and inter-floor* components, in a building are forecast. During the incoming traffic, passengers arrive at the entrance floors or the main entrance, the lobby, and travel to the upper floors. During the outgoing traffic, down calls are given by the passengers who are destined to the lobby, where they exit the building. During inter-floor traffic, passengers travel between the floors inside the building, and nobody enters or exits the building. Figure 3 shows a profile of incoming, outgoing, and inter-floor traffic components forecast by the TMS9000 control system. The statistics were compiled from an office building with common working hours. The morning up-peak is the most difficult situation for the elevator capacity. Special *up-peak boosters* have been developed to increase capacity in this situation. During the lunch hour the passenger traffic intensity is highest and there are a lot of hall calls. This is the most difficult situation for the group control since elevators easily start to bunch. During the intense traffic hours the TMS9000 keeps the elevators evenly spaced by using the Enhanced Spacing Principle. The control utilizes unequal passenger arrival rates and waiting times at the landing floors, and hall calls with short passenger waiting times or a few passengers can be by-passed.

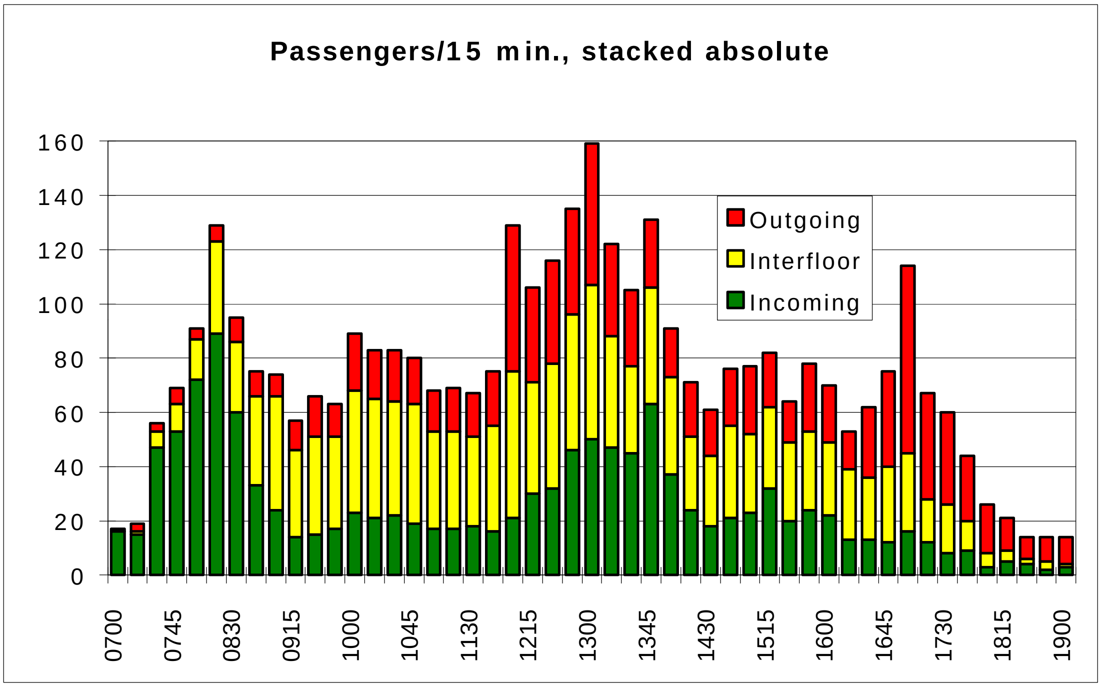


Figure 3. Forecast traffic component profile during a day in an office building in Australia.

3.4 Cost function in multiple target optimization

The choice of optimization target in the cost function is important when considering the overall elevator performance and the service level. The most general optimization target in group controls has been the minimization of the average and maximum hall call times. When only the average call service time is optimized, long "tails" in the hall call time distribution will appear. These tails can be cut by optimizing the average squared waiting time or by giving priorities to the old hall calls. Calls with high priority are given fast service and the long call times are cut. Recently the cost functions have become more comprehensive. Instead of one target, multiple targets are optimized. A number of costs, such as call time, passenger waiting and journey times, car load factor, energy consumption, transportation capacity, and number of starts, can be considered during the call allocation (Fujino et al.1992). The optimization targets are given weights according to the importance of the optimization targets. The weight factors are given, for instance, with an external device by the customer (Tobita et al.1991). When optimizing one target, the other features may suffer. For instance, when optimizing the energy consumption, the passenger waiting times may increase. Several optimization targets can be optimized within one control if the most suitable target is switched according to the prevailing traffic pattern. An application with neural networks automatically searches the best weights for the optimization targets (Sasaki et al. 1996).

3.5 Elevator routing methods

3.5.1 Static allocation of existing calls

Methods of finding optimal routes when delivering existing hall halls to elevators have been investigated since the 1960's. If all the combinations in allocating existing hall calls to elevators were calculated, the combination with the minimum cost would give the global optimum. The problem is that the number of route combinations grows exponentially with the number of hall calls. Consequently, a pure searching method can only be used for a moderate number of elevators and floors. If the search is done for all the combinations of existing hall calls and elevators, the number of unordered route combinations is

$$n_r = L^K \tag{1}$$

where the number of elevators in a group is L and the number of hall calls is K. Hall calls and their allocations to different cars form a decision tree (Publication IV). For each hall call the costs of serving the call by each elevator have to be calculated. The cost of decisions depend on the earlier decisions made for the other hall calls. The global optimum for the cost function is found by calculating all the decision combinations, i.e. elevator routes, in the decision tree. The route with the minimum cost defines the optimal way of allocating the existing hall calls to the elevators.

When hall calls are allocated continuously, the allocation cycle is usually less than half a second. A test was made with the Intel Pentium processor to search all the route combinations for groups of elevators. Within half a second an optimal route was found for three elevators and ten hall calls, and for six cars and six hall calls. These correspond to a buildings with six and three served floors, respectively. In a building with an eight-car group there can be nearly 60 hall calls when all the up and down calls are taken into account. The total number of possible route combinations to be calculated are more than $6.2*10^{57}$. As a conclusion, by searching all the route combinations the global optimum can be found within a reasonable time only for low buildings with 2-3 elevators in the group using the present processing capability.

In order to enhance the calculation time, the number of calculated routes must be considerably decreased. There are common practices in passenger service that restrict the number of possible routes:

1) Car calls are always served sequentially in the travel direction of the elevator, i.e. the elevator will not bypass the destination floor of a passenger.

2) An elevator does not reverse its direction until all the passengers inside the car have been served.

3) Elevators do not accept car calls in the reverse direction of the car travel, i.e. passengers should not enter a car travelling in the opposite direction.

4) Normally a car will stop at a floor only if a passenger wants to board or alight a car. Exceptions are made, for instance, when a car parks at a specific floor during light traffic.

In addition to these practices several approaches have been proposed, such as the use of the ACA algorithm (Adaptive Call Allocation) (Closs 1970). In the ACA algorithm only new calls are allocated to the best cars and the reservations of the existing hall calls remain unchanged. With this method the calculation time is substantially reduced to a practical level in all possible elevator systems. In this method the old allocations can lose their optimality when the final reservation of the hall calls is made at such an early stage.

Another approach to finding the global optimum for the cost function is to use the principle of dynamic optimization with the OR (Optimal Routing) algorithm (Siikonen 1989). In collective control, the nearest hall call for a car is always searched in the travel direction. In the dynamic optimization algorithm, the call allocation order is reversed. The best car for the hall call is searched starting from the furthest hall call in the elevator travel direction. The allocation starts from the lowest call and continues to the highest call. All the hall calls are allocated to the best cars. In the beginning the intermediate stops of the elevators are not known, but after the allocation cycle they are fixed. The allocation is restarted with the new intermediate stop information, and the cycle is iterated until the allocations to the cars remain unchanged. The new control was compared with the ACA algorithm by simulations. When the average call time was used as an optimization target, the new algorithm showed an improvement compared to the results of the ACA algorithm. This algorithm, however, does not always find the global optimum for route combinations.

Recently, genetic algorithms (Alander et al. 1995) and dynamic optimization with reinforcement learning (Crites 1996) have been studied to find optimal elevator routes for existing calls. With these techniques the optimization result depends on the computation time or on years of training the algorithm.

3.5.2 Dynamic call allocation with future event simulation

Attempts have been made to describe the state of a whole elevator system by one expression that includes the states of the elevators, car calls, and hall calls. With this method, the optimization target was to minimize the busy time of the elevators(Levy et al. 1977). The number of states, however, became so large that it was not possible to find the optimum solution in real time. An analogous approach, the OPTICON control, was investigated in co-operation with VTT (Virtamo et al. 1993). During every call allocation cycle a decision is made whether a moving elevator should stop or continue its journey, or a vacant elevator should start, or continue standing with doors open or closed. In this approach the call allocation resembles the decision making in computer chess. Elevator states are simulated during the call allocation for a restricted time in the future. The optimal decision is searched for by varying the future elevator states. The future costs are cumulated in each decision alternative. During the future simulation, passengers arrive randomly at the floors according to the measured or known distribution. Arriving passengers push hall call buttons. Hall calls are allocated by a well-known group control principle, such as by collective control. A call is canceled when a car decelerates to serve the call. Car positions, car calls and car movements are modeled. Several realizations of future passenger traffic are made, and an average cost of all the realizations is calculated. The decision that leads to the minimum cost is chosen. If no hall calls exist, cars will automatically park at the floors with most probable traffic. In this control most of the calculation work is made during light traffic when the number of hall calls is small and the number of decision alternatives is great. During light traffic, elevators move restlessly from one floor to another since hall calls are not used as moments for decision. They are taken into account only indirectly in the cost function.

To remove the restlessness of the previous control the DACA (Dynamically Adaptive Call Allocation) algorithm was developed. The DACA algorithm can be considered as an extension of the ACA. The registration of a new hall call was chosen as the moment of decision, such as in the ACA algorithm. The registration of a new hall call starts the allocation process. The existing hall call is allocated for each car in turn and the same passenger traffic giving hall calls is simulated for some minutes behind the moment the hall call has been served. The ACA algorithm is used in allocating future hall calls to reduce the number of decision alternatives, but any other call allocation algorithm can be applied as well. The existing hall call is reserved for the car with the minimum cumulative cost. More reliable results are obtained than with the ACA algorithm since not only the current situation with existing hall calls is considered but also the effect of future events on the current call allocation. With the DACA algorithm, elevators only move when there are hall calls, which makes it faster than the OPTICON algorithm during light traffic. With both the previous controls, future simulation improved average hall call times in comparison to the controls which consider only existing calls.

4. SIMULATION OF ELEVATOR TRAFFIC

4.1 Elevator traffic simulators

The effect of the group control on the hall call times and on the passenger service level can be determined by simulation. The first elevator traffic simulators were built to test the traffic service in tall buildings, such as the World Trade Center (Browne et al.1968). At that time the group controls in elevator companies were tested with hybrid simulators, which consisted of analog and digital models (Weinberger 1967). In these simulators the real elevator control boards were attached to the traffic simulator. Later, group controls were brought into minicomputers, where various traffic phenomena were studied and clarified (Barney et al. 1985). More recently, the same digital simulators were installed in personal computers (Barney 1988). Usually in personal computers, generic call allocation algorithms are used in the simulators (Lustig 1986). The *Advanced Lift Traffic Simulator*, ALTS, runs on a personal computer. In ALTS, the original group control software was brought from the microprocessor boards to a personal computer, and it was combined with the traffic simulator code. Initially, the ALTS simulator was built for marketing and demonstration purposes. Soon ALTS was adapted as a research tool for developing new group control principles. Different traffic situations can be repeated, which is important for testing purposes. This was not possible with the hybrid simulators, where the delays did not repeat similarly. In this section the main features of the ALTS simulator, and some traffic phenomena found by ALTS simulations, are described. Process models for the passenger traffic generation, the elevator control, the door control and the drive control of the ALTS simulator are described in more detail in Publication II.

4.2 ALTS input data

In ALTS, buildings with a defined number of floors and elevators can be simulated. Before making a simulation the passenger traffic, the building data and the elevator data are defined. Constant values for the door-opening and closing times as well as for the passenger transfer times are used. Measured values for the passenger transfer times normally vary from 1.0 s to 1.7 s. Doors stay open for a basic time if no passengers are transferred. When passengers enter or exit the car, a time called the photocell delay occurs after the last passenger transfer before the doors start to close. The speed of the elevator is updated according to the acceleration and jerk values during a run. In the simulator as well as in a real elevator, automatic doors start to open in advance before the car has fully reached the destination floor (Advanced Door Opening - ADO). The elevator speed during the deceleration and the distance from the destination level are monitored. The doors start to open when the values are below the given limits. Passengers are able to enter or exit the car when the doors are considered to be fully open (800 mm wide). The minimum data required for a simulation by ALTS is shown in Table 1.

Table 1. Minimum input data required for an ALTS simulation.

Building	Traffic	Elevators
Building type	Passenger arrival rate (HC)	Number of elevators
Number of floors	Traffic components	Car sizes
Populated floors	Population distribution	Speeds, accelerations, jerks
Entrance floors	Entrance floor attractions	Door times
Floor heights	Passenger transfer times	Photocell delays ADO speed and distance

4.3 Passenger traffic generation

In the ALTS simulator the passenger traffic can be generated in several ways depending on whether the real traffic is unknown or measured traffic data exist. The desired traffic pattern for the simulation is formed from the shares of the three traffic components, and from the passenger arrival rate. The *100* per cent traffic intensity corresponds to an arrival rate equal to the handling capacity of the elevator group. The passenger arrival times to the floors are generated as uniformly distributed random variables. The arrival and destination floors of individual passengers are random but they follow a given or a measured population distribution in the building. If there are several entrance floors in the building, such as parking floors or metro floors, the relative portions of the arriving passengers at each entrance floor are defined. The simulated passenger traffic flow depends on the building type. In an office building with common working hours there is heavy demand during the morning up-peak, during the lunch hour and during the evening down-peak. A typical lunch-hour traffic is simulated with 40 per-cent incoming, 40 per-cent outgoing, and 20 per-cent inter-floor traffic. In residential buildings and in hotels the traffic consists mostly of incoming and outgoing components.

More detailed parameters for passenger traffic generation can be defined when measured data of the traffic in an actual building exists. The reconstruction of passenger traffic flow depends on how comprehensive the measured data is. With temporarily connected traffic analyzers only the hall calls and elevator stops are usually measured. From the stop information the passenger arrival rate can be deduced with some accuracy. For example, with the inverse S-P method (Al-Sharif 1992) the number of passengers inside the car at the lobby is estimated from the measured number of stops at upper floors. A well-known equation for the expected number of elevator stops during up-peak is reversed when using this method. The number of stops caused by the incoming, outgoing and inter-floor components can be deduced if information on hall and car calls is available. Without the car call information the estimation of the shares of the three traffic components is more inaccurate.

With more sophisticated temporarily connected analyzers the elevator position, the door states and the photocell signals can also be measured. The individual passenger trips can be reconstructed from the measured traffic events by analysing separately each elevator round trip. In laboratory tests an accuracy of 10 % in the passenger traffic intensity was obtained when reconstructing individual passenger trips from the elevator traffic event files (Väljä 1990). For external analyzers, the measurement of car calls requires too much wiring. With built-in elevator monitoring systems, or inside the group control, the car call information is available. With the traffic event data including the car call information a maximum error of 5% was found for the passenger arrival and destination floors (Leppälä 1991).

4.4 Simulation sequence in ALTS

Communication between the control and the simulator occurs through common structures that are updated by all the process models. All the simulated models with their own timings are linked in one task. Any of the models can, however, be run separately in another computer with its own timing sequences (Alander et al. 1994). Many of the elevator traffic processes are discrete, such as arrivals of passengers at floors and call registration and cancellation. In a real computer control, most of the tasks are processed in sequence. For example, the registration of hall calls is “polled” in cycles of milliseconds so that the passenger has to push the hall call button only for a short while to register the call. Some of the processes, such as the elevator speed and position, change continuously as a function of time. Instead of an event-based simulation, the simulation processes in ALTS are divided into small time slices. The simulation proceeds in discrete time steps, ΔT, half a second as a default. The time step is due to the maximum call allocation cycle in real buildings with continuously allocating controls. The process states are updated every time step as time proceeds until a defined simulation time, TMAX, has elapsed. A desired accuracy for the elevator speed and position was obtained by using the four-step Runge-Kutta method (Chapra et al. 1985). Figure 4 shows the execution order of the process models in the simulator. During the simulation, traffic events are logged in a backtrack file and the events can later on be studied with various statistical graphs and tables concerning passenger and call service, lift performance and the elevator round trips.

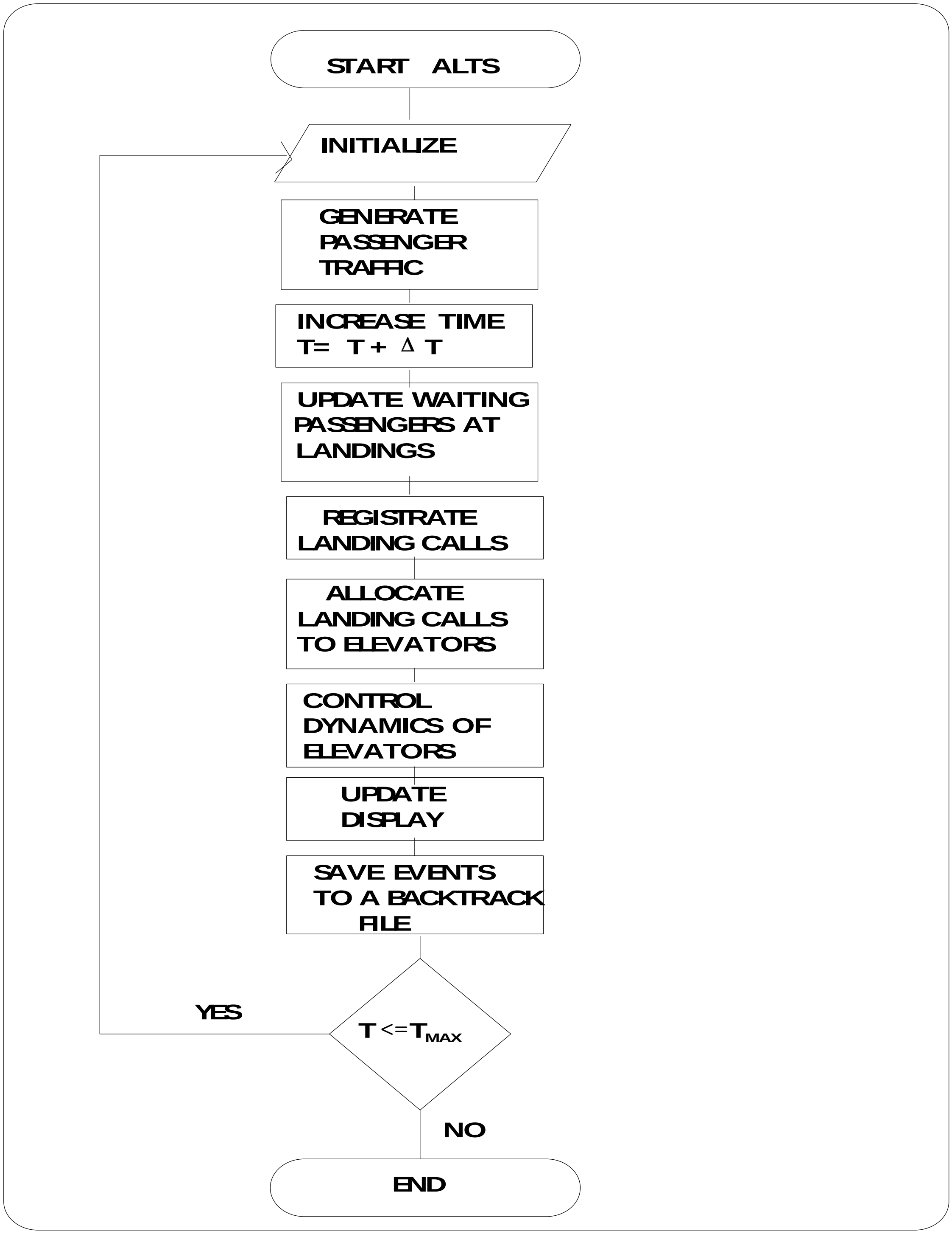
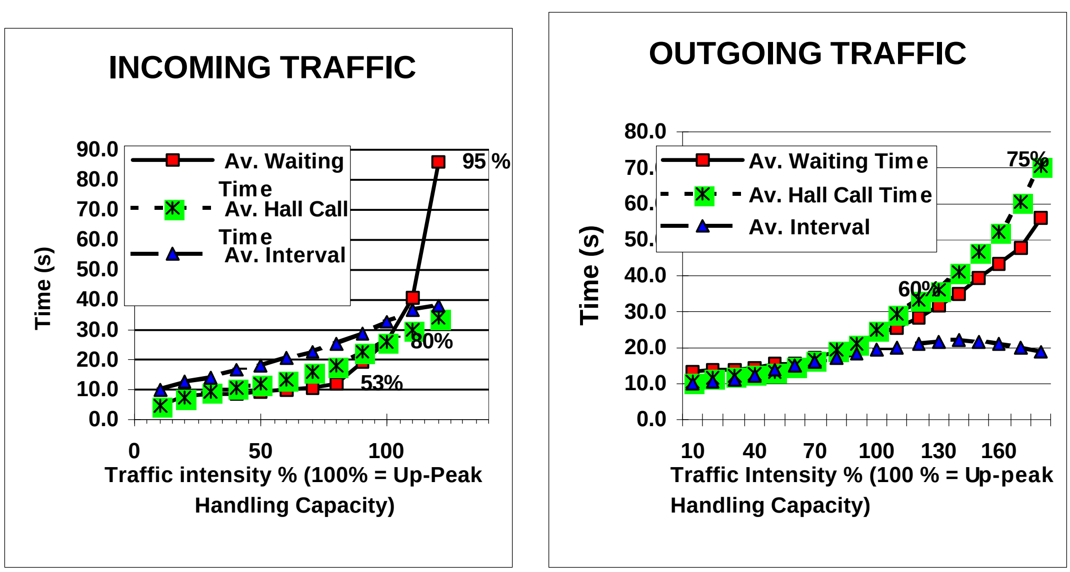


Figure 4. Flow chart of the simulation sequence.

4.5 Simulated passenger traffic phenomena

Correlation between elevator performance and passenger service have been studied with the ALTS simulator. A general approximation is that the average passenger waiting time is half, or three-quarters, of the up-peak interval(BS 5655 1990). This is true in up-peak if elevators and passengers arrive uniformly in time, and the building has only one main entrance floor (Publication III). In a building with multiple entrances the average waiting time during incoming traffic can exceed the interval value. In traffic situations other than incoming traffic, the waiting times depend on the group supervisory control system. Figure 5 shows simulation results for a building with one main entrance. According to Figure 5a, the average waiting time stays below the interval until the passenger arrival rate reaches the handling capacity. In Figure 5b, the average interval, average passenger waiting time and average hall call time are shown for outgoing traffic. The interval for outgoing traffic is shorter than for incoming traffic since the group control can limit the number of stops during outgoing traffic. According to the figures, the average waiting time during the down-peak with 100 % traffic intensity is approximately the same as during the up-peak. During the lunch hour with 100 % traffic intensity the average waiting time is greater than during the down-peak (Publication II). Elevators can transport during the lunch hour traffic about 1.2 - 1.4 times, and during the down peak 1.4 - 1.9 times more passengers in a time unit than during the up-peak period.



(a) (b)

Figure 5. Simulated service level parameters in a building with one entrance floor during incoming (a) and outgoing traffic (b). Numbers beside the curves refer to the car load factor.

5. PLANNING OF ELEVATOR GROUPS

5.1 General planning principles

The selection of the number of elevators, their sizes and speeds is always a compromise between the budget, the building space available and the passenger service level. The investment price of the elevator group consists on many factors, such as the number of cars, car sizes and speeds, the number of landing floors, control options, signalization and car decoration.

Saving the space used by the elevator shafts will pay back its price in the long term. Shaft space can be decreased, for example, by packing more than one car in a shaft. As yet this has been possible only with double-deck elevators. The highest building in the world, completed in 1996, the 450 m high Petronas Tower in Kuala Lumpur, has 88 floors served by *29* double-deck elevators. According to some estimations, a more favorable solution than double-deck elevators for mega high-rise buildings with more than 60-80 floors are single-deck elevator groups with sky lobbies (Jenkins 1993). The building is then divided into zones where shuttle elevators serve the traffic between the main lobby and the sky lobby floors. Large single-and double-deck elevators are used as shuttle lifts. Local zones are served by single-deck elevator groups. The sky-lobby arrangement does not require as much shaft space as in the case where all the elevators leave from the main entrance. The largest shuttle groups are at the moment installed in the New York World Trade Center and in the Chicago Sears Tower (Figure 6). Both the buildings have three local zones with one main entrance and two sky lobbies. Each local zone has four groups of elevators: low-rise (LR), medium low-rise (MLR), medium high-rise (MHR) and high-rise (HR) elevator groups. The number of sky lobbies and shuttle lifts could still be reduced if the local elevator groups served the traffic down from the sky lobby as well. In buildings with more than 20 - 30 stories, the floors are usually divided into zones served by local elevator groups.

When planning elevator groups, sufficient transportation capacity and reasonably short passenger waiting and journey times are guaranteed. Traditionally, three performance parameters are defined, e.g. the handling capacity, the interval, and the travel time. New parameters for elevator planning, the average passenger ride time and the average journey time, are introduced in this section (Publication III). Criteria for the planning parameters are discussed and a new criterion for the average journey time is defined. A criterion can also be set for the passenger service level at the construction stage of a new building. Estimations for the hall call times and for the passenger waiting and journey times are obtained by simulations. The utilization of the ALTS simulator as a tool in integrated elevator planning is described (Publication I). After the installation, elevator group performance and passenger service level can be checked by real-time monitoring systems.

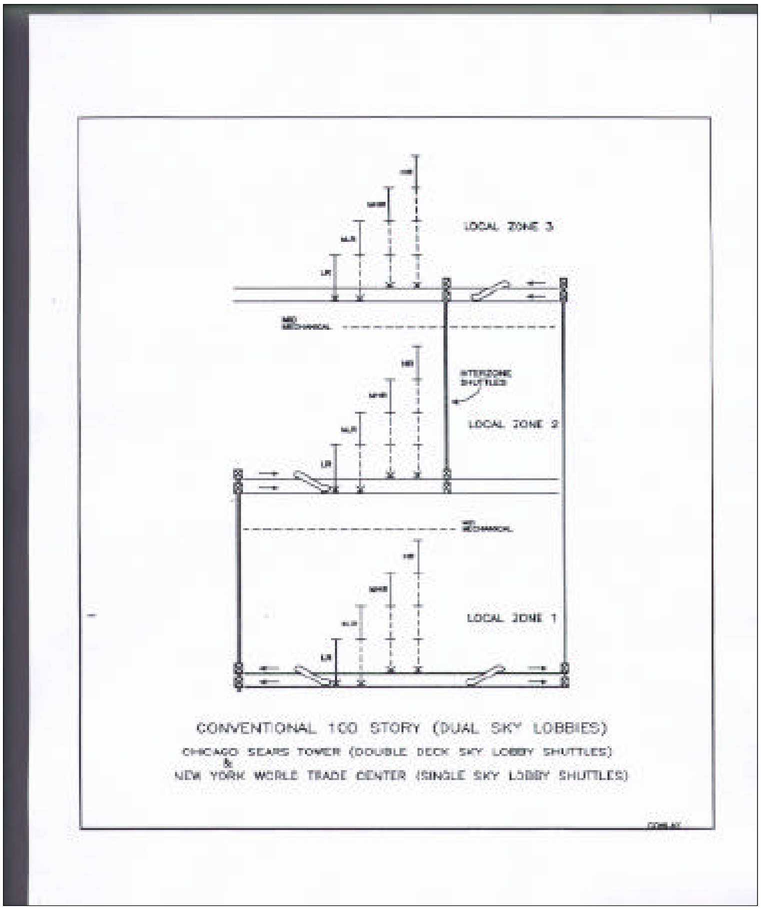


Figure 6. A building with 100 stories and dual sky lobbies (Fortune 1995).

5.2 Conventional elevator planning parameters

The up-peak situation is the most demanding for the elevator handling capacity, as was mentioned in the previous section. The number of passengers the elevator group can transport in five minutes during up-peak is called the *handling capacity*. The relative handling capacity shows how many per cent of the population of the building can be transported in five minutes. To find the handling capacity, the elevator round trip time during up-peak is calculated. The *round trip time* is the time it takes for an elevator to make an up-trip and return back to the lobby. A more general definition for the round trip time in traffic situations other than up-peak is the time between every second reversal of elevator direction. The idle time, i.e. when the car remains vacant, is not included in the round trip time.

The equation for the round trip time during up-peak is based on the number of passengers inside the car when leaving the lobby, and on the population distribution in the building (Jones 1971). The expected number of elevator stops, S, during the up-trip, and the highest reversal floor, H, are calculated to estimate the time elapsed for the elevator stops and for travelling up and back down to the lobby (Tregenza 1971). The first equation for the expected number of elevator stops during the up-trip was derived for a uniform passenger arrival rate and an even population distribution (Jones 1923). In the derivation of the round trip expression it is assumed that the control system is ideal so that the elevators are always evenly distributed in the building. The elevator group is assumed to be in a steady-state so that the cars always leave with the same average load from the lobby. Other assumptions and the derivation of the general form of the round trip time has been described earlier by several authors(Barney 1985). The general form of the round trip time τ is

$$t = 2Ht_v + (S+1)t_s + Mt_M \quad (2)$$

where t_v is the one floor drive time with nominal speed, t_s is the average stop time of the elevator at a floor, M is the number of passengers inside the car when leaving the lobby, and t_M is the passenger transfer time in and out of the car. An equation for the up-peak round trip time which considers the exact running times between floors (Roschier et al.1979) is

$$t = \sum_{r=1}^{N} (T_r + D_r)(t_r + t_d) + Mt_M \quad (3)$$

where T_r and Dr show the expected number of runs covering r floor distances in the up direction and in the down direction, tr is the elevator flight time of a run covering r floor distances, and td consists of the door opening and closing times. Equations for Tr and Dr are based on elevator transition probabilities from one floor to another (Bailey 1954), where a uniform passenger arrival rate was assumed. When passengers are assumed to arrive randomly, the equations for Tr and Dr become more compact, but the value of the round trip time remains about the same (Siikonen 1989). An equation for the handling capacity, HC, derived from the up-peak round trip time is

$$HC = \frac{0.8cL}{t} \quad (4)$$

where c is the car load in persons and L is the number of elevators in a group. When the passenger arrival rate during up-peak exceeds the handling capacity of the elevator group, all the arriving passengers do not fit in a car and the waiting times start to increase rapidly. Another parameter derived from the round trip time is the interval, which is used to give a rough indication of the passenger service level. If there are several elevators in a group, the average *interval* shows the average frequency at which cars leave the lobby for the upper floors during up-peak. If the number of elevators in the group is N, the interval is

$$I = \frac{t}{N} \quad (5)$$

5.3 Mean passenger ride and journey times

An equation for the passenger ride time, τ_r, inside the car during the up-peak is

$$t_r = \sum_{i=1}^{N} T_i / S + (M+1)t_M \tag{6}$$

where the term T_i refers to the expected passenger ride time of the destination floor i (Publication III). The mean ride time is obtained by dividing the sum of the expected ride times to all destination floors by the expected number of stops *S* during the up-trip. The mean of the passenger transfer times during the stops is added to the ride time. This equation is also derived assuming a steady-state situation where the same average number of passengers is carried on each trip. According to the publication, the mean ride time varies from 40 to 70 per cent of the round trip time when the utilization factor, i.e. car load factor, varies between 30 - 80 per-cent. With an *80* per-cent car load factor the mean ride time can be roughly approximated as half of the round trip time. The mean journey time, t^J, consists of the mean passenger waiting time and the mean ride time inside the car. An equation for the mean journey time during up-peak is

$$t_J = q_w / \; l - (k-1)/2m + t_r \tag{7}$$

The first two terms on the right-hand side of the equation refer to the mean passenger waiting time. Parameter q_w is the passenger queue length at the lobby, λ is the passenger arrival rate at the lobby, k/μ is the service time, and k is an arbitrary positive parameter of the Erlang distribution. For a single elevator the mean passenger waiting time can be approximated as half of the round trip time, when the passenger arrival rate is below the handling capacity. For a group of elevators, the Markov M/E(c)/L-model with an exponential service time distribution (k=1) (Alexandris et al. 1979) is in good agreement with experimental results, especially with high utilization factor (passenger arrival rate) values.

5.4 Performance and service level criteria

The same planning methods are used for all types of buildings, only the recommendations for the performance parameter values and service level are different. Similar recommendations are used by the elevator companies, architects and elevator consultants. In low residential buildings, elevators are mostly selected according to a proven practice, but planning calculations are needed in mid- and high-rise buildings with more than 12 - 13 floors.

In a new building, passenger traffic patterns are unknown. Performance recommendations are normally given for the up-peak traffic. It provides sufficient *handling capacity* in all the other traffic situations, as was discussed in Chapter 4.5. International recommendations for the handling capacity exist at least for residential buildings, offices, hotels and hospitals. The filling time of a building during the up-peak, or the evacuation time of the building, are used when deciding the limits for the handling capacity. The filling time of all the people to the building varies from 20 minutes to 100 minutes depending on the type and usage of the building. For example, if the filling time is 20 minutes, it means that 25 per cent of the total population of the building are transported in five minutes. The value of 25 per cent of total population in five minutes provides excellent handling capacity in all types of buildings according to the international practice. In residential buildings the longest filling times are used, approximately 65 - 100 minutes. The handling capacity in residential buildings should exceed 5 - 7.5 per cent, and in commercial buildings 11 - 13 per cent of the population in the building in five minutes (Strakosch 1983).

By using the handling capacity recommendations the size of the elevator system can be defined. The exact number of elevators in a new building is adjusted by the *interval* value. Both the handling capacity and the interval indirectly affect the elevator speed. If the interval remains within a given limit, proper passenger waiting times are guaranteed in a building without special arrangements. The recommended up-peak interval values are standardized. In commercial buildings the average interval should be between 20 - 30 s, in institutional buildings between 30 - 50 s, and in residential buildings between 40 - 100 s (Barney et al.1985).

In addition to the handling capacity and the interval values, a third planning parameter is sometimes used. This parameter is not internationally standardized as well as the handling capacity and the interval. It relates to the time a passenger spends in an elevator system by defining the minimum elevator speed and by restricting the number of served floors. Diverse definitions and the criteria of the third planning parameter are gathered in Table 2. The *travel time* is the time it takes for an elevator to run from the bottom floor to the top of the building at full speed and without any stops on the way. It defines the minimum elevator speed v for travel height h. In office buildings it should be below 32 s and in residential buildings below 50 s (Roschier et al.1971). The *transit time* and the *maximum passenger transit time* to destination define the one-way transit time of the last exiting passenger during up-peak. They should not exceed 150 s for residential and single-tenant buildings, and 180 s for diversified buildings (Strakosch 1984). For passengers leaving from the lobby the average time to destination consists of approximations of the average passenger waiting time and travel time to the mid-point of a served zone. The mean passenger waiting time is approximated as half of the interval and the travel time as one quarter of the round trip time. The *average time to destination* is recommended to stay below 60 s (Fortune 1995). A rough estimation for the average journey time can be given for passenger arrival rates below handling capacity. The mean ride time inside a car is then approximated as half of the round trip time, and the mean waiting time as half of the interval. To be consistent with the earlier definitions in Table 2, the *average journey time* in single-tenant commercial buildings should be somewhere below *100 s*, and below *110 s* in hotels and below *120 s* in residential buildings.

Table 2. Up-peak criteria for a single-tenant commercial building to restrict the time a passenger spends in an elevator system. The interval (I), the round trip time (τ) the nominal speed v, and the elevator travel height (h) values are used.

Parameter	Abbreviation	Approximation	Criterion
Travel time	TR	h/v	< 32s
Transit time	TT	τ-h/v	-
Max. passenger transit time	MPTT	τ/2	< 150s
Average time to destination	ATTD	τ/4+I/2	< 60s
Average ride time	τ_r	τ/2	< 80s*
Average journey time	t_J	τ/2+I/2	< 100s*

* *Suggested*

A fourth criterion used in modern traffic analysis is the *average waiting time*, or in practice often the average *hall call time* or *system response time*. For excellent service level in commercial buildings it is recommended that *98 %* of all the hall call times should be below *60 s* (Fortune 1984). According to the simulations and the elevator traffic measurements, hall call times are exponentially distributed following the Poisson distribution. From the exponential distribution and the previous recommendation it follows that the average hall call time for excellent service level should be below *15 s*.

5.5 Simulation in elevator planning

In existing buildings elevator shafts are already built and their number or sizes cannot be changed. The service level and capacity of old elevators can be improved by modernizing the existing elevators with new components. To find out the improvement potential the performance of the existing elevators has to be measured. Elevator operation times are measured over one, two, three, etc. floor flights until the elevator reaches full speed. The run and door times are measured separately. A quick way to measure the elevator performance is to use a stopwatch. More accurate measurements for the door-to-door performance times and the elevator stop times can be achieved with processor-based devices. Existing hall call times can be measured with temporarily connected traffic analyzers (Lustig 1986; McKay 1980; Roschier et al.1991). After the measurement the hall call times are analysed, and the passenger traffic and the performance parameters can be reconstructed. Using the measured performance data, the effect of current doors or the current drive system on the up-peak interval and on the handling capacity can be calculated. The same calculations are repeated with the performance values of new components. By comparing the performance parameter values of the existing and the new elevators, the improvement potential can be estimated. The improvement in hall call times can be estimated by simulations. A typical improvement in average hall call times has been 40 %, or more, when an old relay-based control has been modernized by a microprocessor control system (Roschier, unpublished). About 20 % is due to the new control system, and the rest 20 % is due to the new doors and drive system. In Figure 7 a scheme of the *Integrated Elevator Planning System* (Kaakinen et al. 1991) is shown. All the planning stages are used only in the most demanding modernization projects.

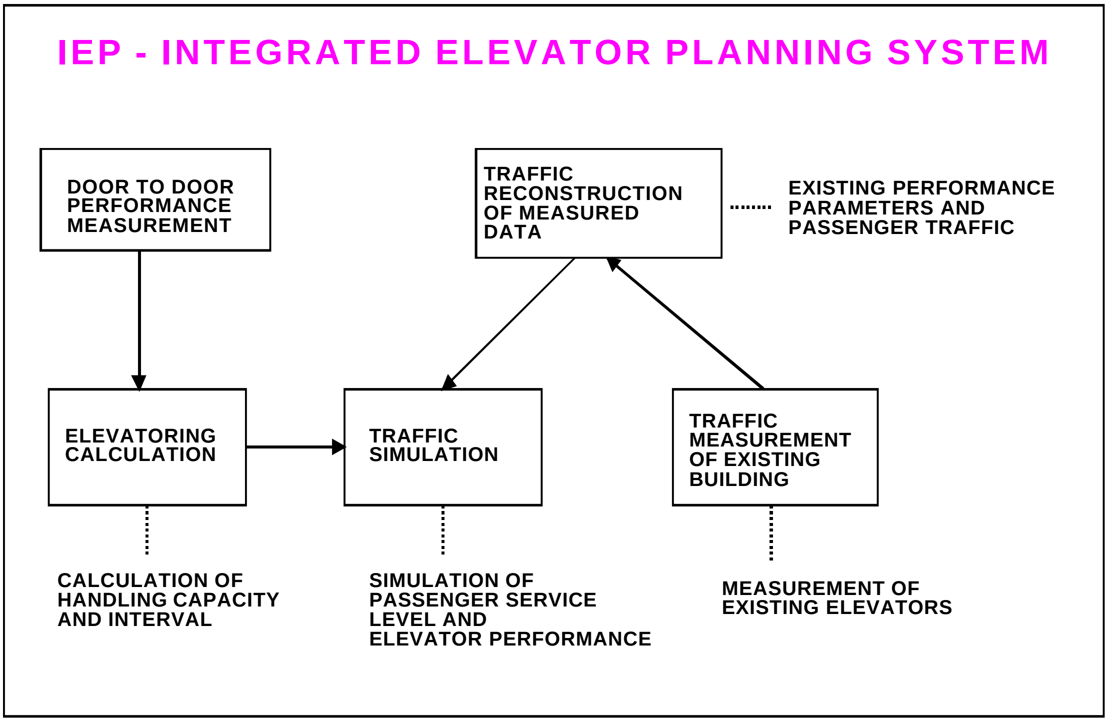


Figure 7. A scheme of the Integrated Elevator Planning System.

6. SUMMARY OF THE PUBLICATIONS

This thesis consists of seven publications on the interaction of passenger and elevator traffic. The real process that keeps the elevators moving, i.e. the passenger traffic, is considered. Earlier, only elevator performance parameters were considered when planning elevators. In this thesis well-known mathematical methods, such as numerical methods for partial differential equations, probability theory, forecasting methods, fuzzy logic and dynamic optimization, are applied. New equations for the round trip time with randomly arriving passengers and unequal running distances, and for the passenger ride and journey times during up-peak were derived. During the work, the elevator traffic simulator, ALTS, and the TMS9000 control system were developed.

In Publication I, the Advanced Lift Traffic Simulator is introduced as a tool in elevator planning. Earlier, only handling capacity, interval and elevator travel time were used as criteria when selecting elevators for a building. The article describes how simulation of passenger waiting times during different times of the day gives additional information in elevator planning.

Publication II introduces the main process models used in ALTS and the validity test of the simulator. Since the 1970’s elevator companies have been using hybrid traffic simulators to test the features of elevator controls. The control boards were attached to mini or mainframe computers. The development of fully digitalized simulators started in universities in the mid of 1970's. The control codes in these simulators were generic. The ALTS simulator was developed in the mid -1980's by the author. In ALTS, the original control software is used and the whole simulation sequence is run on a single personal computer. ALTS is used as a test tool in developing control software as well as a tool in elevator planning.

Publication III introduces new equations for the mean passenger ride time inside a car and for the mean journey time in the up-peak situation. Earlier, passenger time to destination during up-peak was estimated with diverse approximations. The new equation for mean passenger ride time is based on the elevator transition probabilities from one floor to another. In this thesis, a new approximation for the mean journey time is suggested to be nearer to the real mean journey time than the earlier approximations. Planning criteria for the mean journey time are shown in Table 3, and their values are adjusted to be in good agreement with the old criteria in Table 2. In traffic situations other than up-peak, passenger ride and journey times cannot be found in closed form since the control system has a large effect on these times.

Table 3. Up-peak planning criteria for the average passenger journey time, $\tau/2 + I/2$.

Building Type	Criterion
Commercial Buildings	< 100s
Hotels	< 110s
Residential Buildings	< 120s

In Publication IV, the author introduces a new method for optimal elevator routing when serving the hall calls. Normally, the existing calls are optimized to the best elevators. In a dynamic situation future events after canceling the hall call are considered during the call allocation, which improves the optimization result in the long term. In the new method, future hall calls given by probably arriving passengers are considered when allocating a new existing hall call. This is analogous to a chess game, where the future moves have to be considered when making the present decision. The same kind of approach was earlier applied where elevator states were used as a decision moment (Virtamo et al. 1996). By making the decisions only for the new hall calls instead of making a decision every time an elevator changes its state, call allocation becomes more stable and the optimization results are about the same. With the existing technology, simulation of future events still requires too much computation time for a real-time application.

In Publication V the TMS9000 control with artificial intelligence is introduced. In the early 1990's, the interest lay in applying embedded expert systems and artificial intelligence in the most sophisticated elevator controls. The tendency was to compile statistics on traffic events, such as elevator stops and hall and car calls, and to utilize this information in the call allocation. The way the statistics are compiled and utilized is unique for each control. In the TMS9000, a systematic mathematical approach was developed to recognize the traffic pattern from the passenger traffic forecasts by using fuzzy rules. Research work on the statistical forecasts of the traffic started in the mid 1980's (TEKES 1989).For the TMS9000, a new method for counting the number of entering and exiting passengers from car load information (Siikonen et al. 1995), and for forming the statistical forecasts by the Traffic Forecaster (Leppälä 1991) were developed. The compiled statistics by the Traffic Forecaster gives unique information of the passenger traffic intensity levels in real buildings. Hall call allocation is based on the Enhanced Spacing Principle (ESP). This principle had already been used in a mid-rise TMS control system to optimize hall call times, but in the TMS9000 it was further developed to optimize passenger waiting times (Kontturi et al. 1997). A method using fuzzy rules was developed to predict the traffic pattern (Siikonen et al. 1993). With this method, traffic patterns change smoothly from one to another, and control operations can be started in advance compared to conventional controls. The TMS9000 control system was finalized in 1991 and it became the second -generation microprocessor control system in KONE for high-rise buildings.

Publication VI is the first publication of the TMS9000 and concentrates to describe the "artificial intelligence" (Traffic Forecaster). It describes the method how fuzzy logic is used to recognize the passenger traffic pattern from the statistical forecasts in a building.

Publication VII is a general publication of the implementation of the TMS9000 control system. It compares the same control without and with artificial intelligence. With an example it is shown that the maximum waiting times at the busy floors are decreased and average waiting times are balanced floor by floor when using artificial intelligence. The TMS9000 control system with artificial intelligence is effective especially in buildings with uneven passenger arrival rates at different floors and in different directions.

7. CONCLUSIONS

The goal of this work was to add the passenger perspective to the control and planning of elevators in multiple shafts. The passenger traffic in a building is divided into incoming, outgoing and inter-floor traffic components. With these three components, traffic in a building can be defined more comprehensively than with the definition of conventional up and down traffic. These basic definitions have been adapted in the ALTS simulator and they are also used in the TMS9000 control system to define the traffic pattern.

The service level of old relay systems have been measured with elevator traffic analyzers. According to the measurements the traffic repeats a pattern quite consistently from day to day in most buildings. Thus the peak traffic hours and peak traffic floors can be forecast according to the historical data. In the TMS9000 control system, the information on the passenger traffic flow in the building is learned for every weekday. Passengers using the elevators are not aware of the measurement, and they do not have to get used to new practices, such as destination buttons. According to the simulation tests, the TMS9000 control system improves the passenger service level in commercial buildings especially during peak traffic hours when the passenger arrival rates at different floors and directions vary. A practical example where an old electronic control system was modernized with the TMS9000 control system showed an improvement of about 35-40 % in average hall call times. The improvement in passenger waiting times is about the same since passenger waiting times correlate with call times when the traffic intensity stays below handling capacity.

In the future, more sophisticated call allocation algorithms will be developed and new optimization targets will be found. In optimizing a single target, such as the average hall call time, a limit exists at which new call allocation algorithms do not bring much improvement. The present tendency is to pay attention to several items simultaneously, such as to improve passenger service and comfort level, to increase handling capacity and to save of energy, ropes and other elevator equipment. By minimizing passenger journey times, also waiting times, ride times and the number of stops are minimized. Often the optimization targets are in conflict with each other, and they cannot be achieved simultaneously. To make elevators ride smoothly their acceleration and jerk values have to be decreased, which increases passenger waiting times and reduces handling capacity. If low acceleration and jerk values are taken into account already when defining the elevator handling capacity in a new building, good ride comfort and short waiting times can be achieved simultaneously. One way to achieve as many optimization targets as possible is to change the weights of the optimization targets according to the traffic pattern during the day.

In elevator planning, the number, size and performance of the elevators are mostly determined by two planning parameters: the up-peak handling capacity and interval. In an elevator group with several elevators, the handling capacity may be good and the interval may be short, but the round trip time and passenger ride time inside the car may be long. Instead of the interval, more comprehensive and understandable criteria would be to use the average passenger waiting and journey times in up-peak. For the average passenger waiting time, half of the interval value and criteria could be used even though they give rough estimations of the average waiting time. By using the average journey time in elevator planning, the total time a passenger spends in an elevator system would remain short. In a high-rise building the journey time criterion sets a limit on the number of floors served by an elevator group.

The present work is based on the assumption that each elevator occupies one shaft. Currently, the construction of mega high-rise buildings with heights in excess of 450 m has promoted the development of ropeless elevators (Kamaike et al. 1991; Kim et al. 1993). Building core space would be saved if only one shaft were required for the up and another for the down direction for as many elevator units as needed. These kinds of concepts arouse interesting speculations as to how the transportation and control of the traffic in buildings should be planned to provide the best service most economically. In a single-shaft system, the planning of elevators would not be as critical as in the present systems, since handling capacity could be increased later by adding the required number of cars in the shaft. Elevators could be supervised by a group control, or they could be handled as trains, independently moving cars or robots. In these circumstances the whole elevator control system should be reconsidered. However, the main process, the passenger traffic flow in a building and the transportation demand, is not affected by the elevator system. The statistical forecasts and mathematical methods applied to the passenger traffic analysis in this thesis remain valid even if the elevator configuration and control were greatly changed.

REFERENCES

Aalto, S., Odotuskustannusten minimointi joukkopalvelvussa jonossa, Lic. Thesis, University of Helsinki, 1995. 109 p.

Alander, J.T., Ylinen, J., Tyni, T. Optimizingelevator control parameters, Proceedings of the Second Finnish Workshop on Genetic Algorithms and Their Applications, Vaasa, Finland, 1994.

Alexandris, N.A. Statistical models in lift systems, Ph.D. Thesis, University of Manchester Institute of Science and Technology, 1977. 252p.

Alexandris, N.A., Barney, G.C., Harris, C.J. Multi-car lift system analysis and design, Appl. Math. Modelling, 1979, Vol.3,No.8,pp. 269-274.

Al-Sharif, L. New concepts in lift traffic analysis: the inverse S-P (I-S-P) method, Elevator Technology 4. Stockport, England: IAEE Publications, 1992. pp. 8-17. ISBN 0-9513498-5-6.

Aoki, H., Sasaki, K. Group supervisory control system assisted by artificial intelligence, Elevator World, 1990. No. 2, pp. 70-80.

Bailey, N. T. J. On queuing process with bulk service, Journal of the Royal Statistical Society, 1954. Vol. 16, No. 1, pp. 80-87.

Barney, G. C., dos Santos, S. M. Elevator traffic analysis, design and control, Peter Peregrinus Ltd., UK, 1985. 386 p.

Barney, G. C. Lift simulation using PC's, Proceedings of ELEVCON '88, IAEE, Karlsruhe, W. Germany, 1988. pp. 22-29.

Barney, G. C. Vertical transportation standards, Elevatori, 1995. No.7-8, pp. 109-114.

Bittar, J., Mendelsohn, A. Variable elevator up peak dispatching interval, U.S. Patent No. 4 305 479, 1981.

Browne, J. J., Kelly, J. J. Simulation of elevator system for world's tallest buildings, Transportation Science, 1968. Vol.2, No. 1, pp. 35-56.

BS 5655. Lifts and service lifts, Part 6. Code of practice for selection and installation, British Standard , 1990. 44p.

Chapman, J. Supervisory panels from passenger to building management, Elevator World, 1994. No. 3, pp.57-61.

Chapra, S. C., Canale, R. P. Numerical methods for engineers with personal computer applications, McGraw-Hill Book Company, 1985. 570p.

Closs, C. D. The computer control of passenger traffic in large lift systems, The Victoria University of Manchester, Ph.D. Thesis, 1970. 106p.

Crites, R. H. Large-scale dynamic optimization using teams of reinforcement learning agents, Ph.D. Thesis, University of Massachusetts, Computer Science, 1996. 104p.

Fortune, J. W. Elevatoring high rise buildings, International Conference on Tall Buildings, Singapore, 1984.

Fortune, J. W. Mega high-rise elevators; They could be hazardous to your health, Habitat and the High-Rise, Proceedings of the Fifth World Congress, Council on Tall Buildings and Urban Habitat, Amsterdam, Holland, 1995. pp. 661-676.

Fujino, A., Tobita, T., Yoneda, K. An on-line tuning method for multi-objective control of elevator group, ISBN 0-7803-0582-5/92, International Conference on Industrial Electronics, Control, Instrumentation and Automation, Second Volume, San Diego, CA, U.S.A., 1992. pp. 795-800.

Hakala, H. Applications of linear motors in elevator hoisting machines, Ph.D. Thesis, Tampere University of Technology, 1995. 152p.

Hirasawa, K., Kuzunuki, S., Iwasaki, T., Kaneko, T. Optimal hall call assignment method of elevator group supervisory control system, Joint Automatic Control Conference, USA, 1978. pp. 305-313.

Jenkins, K. Structures and elevators, Elevator World,1993.No.1,pp. 48-59.

Jones, B. The probable number of stops made by an elevator, General Electric Review, 1923. Vol. 26, No. 8, pp. 583-587.

Jones, B. W. Simple analytical method for evaluating lift performance during up peak, Transportation Researech, 1971. No. 5, pp. 301-306.

Kaakinen, M., Roschier, N-R. Integrated elevator planning system, Elevator World, 1991. No. 3, pp. 73-76.

Kamaike, H., Ishii T., Watanable E., Matsukura Y. A ropeless linear drive elevator, Elevator World, 1991. No.3, pp. 42-43.

Kameli, N. Intelligent elevator dispatching systems, AI Expert, 1989. No. 9, pp. 32-37.

Kawano, S., Yuminaka, T., Kobayashi, N. Remote and intelligent diagnostic system for elevators incorporating preventive maintenance, Elevator World, 1994. No. 5, pp. 66-71.

Kim, H. J., Takasi, Y., Torii, S., Watada, M., Ebihara, D. Study of the rope-less elevator with linear synchronous motor, International Conference on Electrical Machines in Australia, Adelaide, Australia, 1993. pp. 439-444.

Kontturi, R., Siikonen, M-L. Procedure for controlling an elevator group, KONE Elevator, U.S. Patent No. 5 616 896, 1997.

Levy, D., Yadin, M., Alexandrovitz, A. Optimal control of elevators, International Journal Systems Science, 1977. Vol. 8, No. 3, pp. 301-320.

Leppälä, J. Forecasting passenger traffic in group control of elevators, Helsinki University of Technology, Master of Science Thesis, 1991. 75p. (In Finnish)

Lustig, A. Lift simulation program, Elevator World, 1986. No. 3, pp. 74-79.

Lustig, A. A data logger for lift engineers, Elevator World, 1986. No. 8, pp. 55-59.

McKay, E. M. A data logger for lift traffic engineering, Elevator World, 1980. No. 1, pp. 20-26.

Nakai, S., Kubo, S., Imasaki, N., Yoshitsuku, T., Kiji, J, Endo, T. Elevator group control system with fuzzy neural network model, The Fourth IEEE International Conference on Fuzzy Systems, Yokohama, Japan, 1995. pp. 37-38. ISBN 0-7803-2461-7/95. NEII Vertical Transportation Standards, National Elevator Industry, Inc. Performance Standards Committee, 7th edition, 1994. 42p. 185 Bridge Plaza North, FT. Lee, NJ 07024, 201-944-3211.

Powell, B. A. Important issues in up peak traffic handling, Elevator Technology 4, Proceedings of ELEVCON'92, Amsterdam, Holland, 1992. pp. 207-218.

Powell, B. A., Sirag, D., J. Fuzzy logic - A new way of thinking about the complexities of dispatching elevators, Elevator World, 1993. No. 9, pp. 78-84.

Roschier,N-R.,Kaakinen,M.,J. New fmulae or elevator round rip calcu-lation, Supplement to Elevator World for ACIST members,1979.pp. 189-197.

Roschier, N-R., Virkkala, V. Planning of lift systems, Internal Publication of Kone Corporation, 1971.

Roschier, N-R., Kangas, P., Korpela, J. Lift traffic analyzer LTA-3, User manual for logging, Internal Publication of Kone Corporation, 1991.

Roschier, N-R. Modern elevator traffic planning methods, KONE Elevators Research Center, unpublished.

Sakai,Y., Kurosawa,K. Development of elevator supervisory group control system with artificial intelligence,Hitachi Review,1984.Vol.33, No.1, pp. 25-30.

Sasaki, K., Markon, S., Nkagawa, M. Elevator group supervisory control system using neural networks, Elevator World, 1996. No. 2, pp. 81-86.

Schröder, J. Pocket computer elevatoring - Optimizing for minimum cost, Elevator World, 1984. No. 2, pp. 19-20.

Schröder, J. Advanced dispatching - Destination hall calls + instant car-to-call assignment: M10, Elevator World, 1990. No. 3, pp. 40-46.

Siikonen, M-L. Computer modelling of elevator traffic and control, Helsinki University of Technology, Licentiate Thesis, 1989. 75p. (In Finnish)

Siikonen, M-L., Korhonen, T. Defining the traffic mode of an elevator, based on traffic statistical data and traffic type definitions, KONE Elevator, U.S. Patent No. 5 229 559, 1993.

Siikonen, M-L., Roschier, N-R. Determination of the number of persons entering and leaving an elevator car, KONE Elevator GMBH, U.S. Patent No. 5 435 416,1995.

Strakosch, G. R. Vertical transportation:elevators and escalators, John Wiley & Sons, Inc, 1967. 495p.

Strakosch, G. R. Improve your elevatoring capability - Part I, Elevator World, 1983. No. 11, pp. 3-4.

Strakosch, G. R. Improve your elevatoring capability - Part IV, Elevator World, 1984. No. 2, pp. 8-9.

TEKES Artificial intelligence, Tietotekniikan kehittämisohjelma FINPRIT, 1989. pp. 63-80.(In Finnish)

Tobita, T., Fujino, A., Inaba, H., Yoneda, K., Ueshima, T. An elevator characterized group supervisory control system, International Conference on Industrial Electronics, Control and Instrumentation, Japan, 1991. pp. 1972-1976. ISBN 0-87942-688-8.k

Tregenza, P. R. The prediction of lift performance in multi-storey buildings, Ph.D. Thesis, University of Nottingham, 1971. 138p.

Umeda, Y., Uetani, K., Ujihara, H., Tsuji, S. Fuzzy theory and intelligent options, Elevator World, 1989. No. 7, pp. 86-91.

Virkkala, V. Hissitekniikan perusasioita, Internal Publication of Kone Corporation, 1983. 153p. (In Finnish)

Virtamo, J., Aalto, S. Procedure for controlling an elevator group, KONE Elevator GMBH, US Patent No. 5 503 249, 1996.

Väljä, M. Modelling of passenger traffic based on measurements with an elevator group, Helsinki University, Master of Science Thesis, 1990. 103p. (In Finnish)

Weinberger, W. A lift traffic simulator, Födern und Heben, 1967. Vol. 17, No. 16, pp. 923-925.