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FOREWORD

It is with great pleasure that we present the proceedings of the 4th Symposium on Lift and Escalator Technologies, September 2014, organised jointly by The Lift Engineering Section of the School of Science and Technology and The CIBSE Lift Group.

The Lift Engineering programme offered at The University of Northampton includes postgraduate courses at MSc/ MPhil/ PhD levels that involve a study of the advanced principles and philosophy underlying lift and escalator technologies. The programme aims to provide a detailed, academic study of engineering and related management issues for persons employed in lift making and allied industries.

The CIBSE Lifts Group is a specialist forum for members who have an interest in vertical transportation. The group meets regularly to promote technical standards, training and education, publications and various aspects of the vertical transportation industry. The CIBSE Lifts Group directs the development of CIBSE Guide D: Transportation systems in buildings, the de facto reference on vertical transportation.

The Symposium brings together experts from the field of vertical transportation, offering an opportunity for speakers to present peer reviewed papers on the subject of their research. Speakers include industry experts, academics and post graduate students.

The papers are listed alphabetically by first author details. The requirement was to prepare an extended abstract, but full papers were accepted from the invited speakers where they preferred to offer them. The submissions are reproduced as they were submitted, with minor changes in formatting, and correction of obvious language errors where there was no risk of changing meaning.

We are grateful to organisations that have supported this venture, as highlighted by their logos below.

Professor Stefan Kaczmarczyk, The University of Northampton and
Dr Richard Peters, The CIBSE Lifts Group

CONTENTS

A New Paradigm for Assessing the Effectiveness of Up-Peak Group Control Algorithms

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Abstract. Elevator group control is critical to the optimal operation of elevator traffic systems under general traffic conditions. In the last 20 years, new elevator group control algorithms have become available for use under up-peak traffic conditions. These up-peak algorithms can be generally classified into three categories: static sectoring, dynamic sectoring and destination group control.

It is customary to use simulation to assess the effectiveness of group control algorithms. This paper offers a new approach, which is built around numerical methods.

Numerical methods can be used to objectively assess the effectiveness of an up-peak group control algorithm by subjecting the group controller to a large number of random scenarios. Each random scenario comprises a set of randomly generated passenger destinations. The performance of each scenario is recorded and the average performance of all the scenarios is used as an indicator of the effectiveness of the algorithm.

The conditions under which the scenarios are run and the algorithms executed can gradually move from the fully idealised conditions to the fully realistic conditions. There are a number of benefits to this approach which will be outlined in the paper.

1   INTRODUCTION

Elevator group control is probably the most important mathematical problem to solve in elevator systems. It is a very demanding task as it has, even for the simplest of situations, an excessively large number of possible solutions. The aim of the elevator group control algorithm is to find the solution that optimises a certain parameter of interest. The optimisation could involve one or more of the following: maximising the handling capacity, minimising the average waiting time or the average travelling time.

Elevator group control is only applicable to systems having two or more elevators operating in the same group. They have a common set of landing calls. The function of the group controller is to allocate the landing calls as soon as they are registered to one (and only one) of the elevators in the group, in order to minimise one or more of the parameters above. It is usually not possible with destination control systems to de-allocate the landing call from the elevator and re-allocate it to a different elevator in case a better allocation becomes available.

Moreover, the decision on the allocation of a new landing call to a specific elevator in the group has to be taken within a very short period of time (usually less than 500 ms) with destination group control. This places a large burden on the elevator group real time controller.

With the proliferation of new elevator group control algorithms, it has become necessary to objectively assess and compare these different group control algorithms. This is critical to the successful design of the vertical transportation system for a building, independently of the specific

implementations that the suppliers adopt. Simulation has traditionally been the tool used to do so. This new paradigm can complement simulation in many areas.

This paper suggests a new paradigm for assessing up peak group control algorithms. It is based on two pillars: numerical scenario testing (NST) and progressive introduction of reality (PIR).

Section 2 provides an overview of the generic classifications of the elevator group control algorithms. The first pillar of the new paradigm is introduced in section 3, called the Progressive Introduction of Reality (PIR). Numerical Scenario Testing (NST) is the second pillar of the new paradigm and is introduced in section 4. Some advantages of the new paradigm are listed in section 5. Section 6 previews some results from the application of the method for a sample building. Conclusions are drawn in section 7.

2   ELEVATOR GROUP CONTROL ALGORITHMS

Group control algorithms can be sub-divided into two main categories in accordance with the type of prevailing traffic as follows:

1.   General traffic group control algorithms: These group control algorithms are applied under any mix of traffic patterns (incoming; outgoing; inter-floor). Although some of the ideas presented in this paper could be applied to these group control algorithms, this will not be discussed in any detail in this paper as it is thus beyond its scope.

2.   Up-peak Group Control algorithms: These group control algorithms are used in cases where the main component of passenger traffic is entering the building from the main entrance and heading to the occupant floors above. This group of group control algorithms is discussed in more detail below.

It has usually been accepted that once an up-peak situation has been detected or manually selected there is very little that the group controller can do under the conventional up peak conditions other than two obvious actions. These two actions consist of returning the cars back to the main terminal as soon as they have delivered the passengers to their destinations; and controlling the status of the doors of any cars present at the main terminal in order to fill up one elevator car at a time and allow it to depart and then open the doors of other waiting cars one at a time.

However, this has changed with the introduction of a number of up-peak group control algorithms, such as static sectoring, dynamic sectoring and destination group control.

In static sectoring [1], the building is split up during the up-peak period into a number of sectors where each sector contains a number of contiguous floors having equal populations. Every time an elevator arrives at the main terminal, the elevator is assigned to a certain sector, and this is communicated to the waiting passengers at the main terminal. Dynamic sectoring operates in a similar way but with the difference that the sizes of the sectors change continuously ([2], [3], [4], [5], [6]).

Destination group control systems allow the passengers to register their destinations prior to boarding the elevator ([7], [8], [9], [10], [11]). The group control system can thus allocate the landing call to the most suitable elevator in the group and inform the passenger waiting in the lobby. As the elevator has more information, it is possible to make a better allocation decision.

The three algorithms provide an improvement in handling capacity of the elevator system. This boost attains it largest value under up peak traffic conditions ([12], [13]). The methodology outlined in this paper is suitable for assessing and comparing these three elevator group control

algorithms, although the examples given have been restricted to the case of destination group control.

3 PROGRESSIVE INTRODUCTION OF REALITY (*PIR*)

The first pillar that this new paradigm is based on is the concept of Progressive Introduction of Reality (*PIR*). The results of the assessment under fully idealized conditions are referred to as the Idealised Optimal Benchmark (*IOB*) which has been discussed in more detail in [12]. The *IOB* offers an upper limit on the performance to which all subsequent results can be compared. As real life conditions are introduced, the general rule is that the performance of the system deteriorates.

The various parameters or conditions that can be varied are shown diagrammatically in Figure 1, where fully idealized conditions are shown on the left hand-side, while real life conditions are shown on the right hand side. Of particular interest is the condition of assessing the parameters using one round trip time as the analysis workspace as opposed to using a longer period of time as the analysis workspace, where this condition is particularly important when assessing the value of the average waiting time using Monte Carlo simulation.
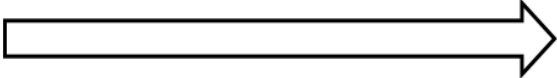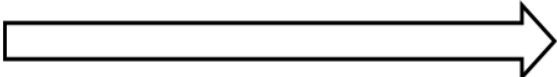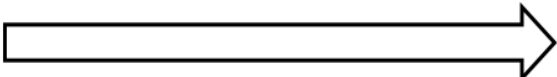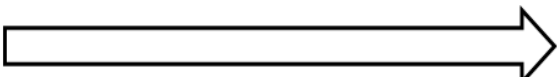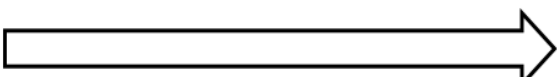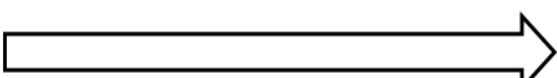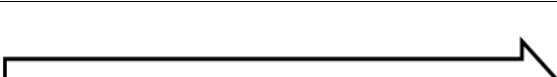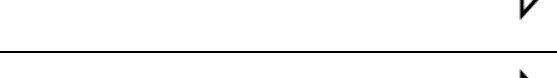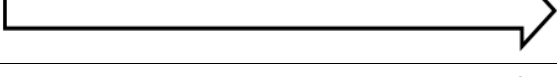
IDEALISED CONDITIONS	progressive introduction of reality (PIR)→	REAL LIFE CONDITIONS
Constant arrival process		Poisson arrival process
No bunching of elevators		Bunching of elevators
No group control		Effect of group controller
Incoming traffic only		Mixed traffic conditions
Single entrance		Multiple entrances
Workspaces equal to one round trip time		Workspaces equal to full simulation time
Full advanced knowledge of passenger destinations		No advanced knowledge of passenger destinations
Infinite processing power of the controller assumed		Limited on-line processing power
Offline processing of the assignment of calls		Real time assignment of calls
IDEALISED CONDITIONS	progressive introduction of reality (PIR)→	REAL LIFE CONDITIONS

Figure 1: Diagrammatic representation of the concept of progressive introduction of reality (PIR).

The concept of *PIR* has also been applied in deriving a formula for the round trip time, starting from the case of single entrance, incoming traffic, equal floor heights in [14], moving to multiple entrances, incoming traffic, equal floor heights in [15], moving to multiple entrances, incoming traffic, unequal floor heights, top speed not attained in one floor journey in [16] and then ending with multiple entrance, mixed traffic condition, unequal floor heights and top speed not attained in one floor journey in [17].

4   NUMERICAL SCENARIO TESTING (*NST*)

This section outlines the methodology used for assessing the destination group control algorithm under up peak conditions ([12], [13], [18], [19]). As shown in [20] in detail, the number of possible combinations is astronomically large. It is thus not practical or realistic to list all of the possible scenarios and to enumerate every possible solution to each scenario.

A more practical solution is to take a sample of the possible scenarios using Monte Carlo simulation, and then to solve each scenario using heuristics or rules of thumb. It is also possible to solve the scenarios using other optimisation techniques (e.g. single step and multi-step random searches). These solution methods are not intended in any way to be used in real time elevator group control systems, but they are used for off-line evaluation studies.

The following are the steps followed in assessing a group control algorithm using numerical methods:

  i.   Generate a new possible scenario: A new scenario is generated using a random scenario generator. This is done by randomly assigning each passenger to a floor with the probabilities linked to the floor populations.

  ii.   For each of the possible scenarios generated in i above, find the most suitable solution by using heuristic (rule based) methods or by using random search techniques. The solution will show an allocation of the $L{\cdot}P$ passengers to the L elevators. The solution will attempt to optimise a certain parameter (e.g., the smallest value of the round trip time and hence the largest handling capacity).

  iii. Steps i and ii are repeated until a large number of scenarios have been considered (e.g., 100 000 or 1 000 000).

  iv.   Once done, the average value of the best solution for all the scenarios is calculated and is used as a representative assessment of the group control algorithm.

When considering an elevator group control such as destination for example, there are a number of methods in which the $L{\cdot}P$ passengers can be allocated to the L elevators. These methods fall mainly into two broad categories: Random searches and rule based algorithms. Examples are given below:

  a)   Fixed step size random search. Using this tool, the software randomly makes a single change in the allocation by swapping the allocation of two passengers to two different elevators. If the optimisation target is reduced, then the swap is retained; otherwise it is rejected. This process is repeated until no more improvement can be achieved after a certain number of steps.

  b)   Rule based allocation. Using this tool, a set of rules guides the user to splitting the sectors in the building such that the target parameter is optimised.

5   ADVANTAGES OF THE PARADIGM

Using this paradigm for assessing the effectiveness of up-peak group control algorithms offers the following advantages, among many others:

1. The effect of each introduction of a reality condition can be assessed independently of the other changes. This can be insightful to the designer of the algorithm in understanding the impact of each condition, and can be helpful in guiding the designer of the algorithm to make useful changes.

2. The numerical scenario testing is transparent and can be easily described by the use of rules and heuristics, allowing reproducibility.

3. It provides an overall limit on the performance of the algorithms, and thus the designer need not spend too much time on trying to improve an algorithm that is very near the benchmark.

6   SAMPLE RESULTS

A sample of the results found so far will be given in this section for destination group control. In assessing the destination group control algorithm operating under peak traffic conditions, four distinct stages can be traversed in moving from idealised conditions to real life conditions, as shown in Figure 2 below. The first stage is to develop an idealised optimal benchmark using equations. The next stage is generating random scenarios and solving them offline, assuming perfect advanced knowledge of the passenger destination. This is referred to as offline allocation of landing calls. The next stage is real time allocation of the landing calls, where only one landing call is revealed to the controller at a time. The final stage is real time simulation of the whole system, which then takes into consideration the movement of the elevator cars. The boost in handling capacity progressively deteriorates with the transition at every stage.
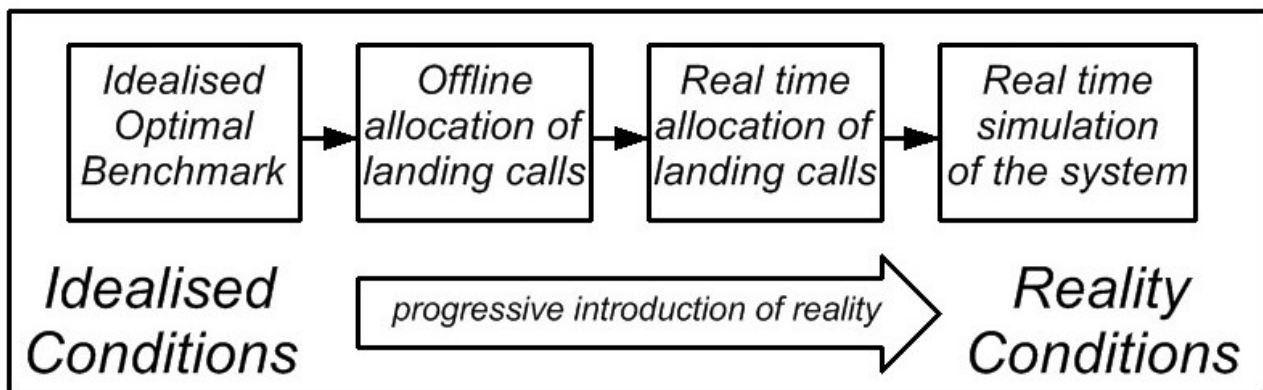
Figure 2: Applying the concept of PIR to the analysis of the performance of destination group control algorithms.

This has been applied to a single entrance sample building that has the parameters shown in Table 1 below.

Table 1: Sample building used.

Number of Elevators in the group (L)	4
Number of Passengers in the Car (P)	7
Number of floors above the main entrance (N)	10
Total building population (U)	600
Floor height in m (d_f)	4.2

The boost in handling capacity compared to the conventional group control has been used as the benchmark for comparison of the effectiveness of each reality condition. The boost in handling capacity has been shown for the benchmark, offline allocation and real-time allocation of calls in Table 2, where the boost in handling capacity with the IOB is 148% (i.e., an increase of 48%). Full details of the workings of the real time allocation and the effect of the number of elevators in the group can be found in [21].

Table 2: Sample results for a building under destination group control that aims to minimise the average round trip time or maximise the handling capacity of the system assuming contiguous equal size sectors.

Algorithm/Equation	Boost in Handling Capacity under destination compared to conventional group control
Idealised Optimal Benchmark (*IOB*) [12]	148%
Minimisation of *H* then *S (offline allocation)* [13]	142%
Minimisation of *H* only *(offline allocation)* [13]	140%
Minimisation of *S* only *(offline allocation)* [13]	134%
Real time allocation [21]	125%

7   CONCLUSIONS

Elevator group control algorithms can be generally sub-divided into general traffic condition algorithms and up-peak traffic condition algorithms. The up-peak group control algorithms can be further sub-divided into three types: static sectoring, dynamic sectoring and destination group control algorithms.

Simulation has traditionally been used as the tool for assessing the effectiveness of elevator group control algorithms. This paper presents a suggested new paradigm that relies on the use of numerical scenario testing (*NST*) and progressive introduction of reality (*PIR*) in order to assess the effectiveness of up peak group control algorithms. Under numerical scenario testing, the Monte Carlo simulation method is used whereby random passenger destinations are generated and the optimum solution is found for each scenario and recorded. The average of all the large number of trials is then calculated and used as representative of the performance of the algorithm, under the conditions assumed. The progressive introduction of reality starts the analysis under the most ideal conditions and then progressively changes the conditions to more real life conditions.

The advantages of this new paradigm is that it is fully transparent thus allowing reproducibility, provides insights to the algorithm designer regarding the effect of different conditions on the effectiveness of the algorithm and provides an upper limit benchmark that no algorithm can ever surpass.

Results were presented for a sample building in which the method was applied for the assessment of an algorithm for destination group control. The resultant boost in handling capacity was 148% under the idealised conditions and dropped to 125% for the real time allocation of landing calls conditions.

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BIOGRAPHICAL DETAILS

Lutfi Al-Sharif received his Ph.D. in lift traffic analysis in 1992 from the University of Manchester. He worked for 9 years for London Underground, London, United Kingdom in the area of lifts and escalators. In 2002, he formed Al-Sharif VTC Ltd, a vertical transportation consultancy based in London, United Kingdom. He has 17 published papers in peer reviewed journals the area of vertical transportation systems and is co-inventor of four patents. He is currently Associate Professor in the Department of Mechatronic Engineering at The University of Jordan, Amman, Jordan.

Modelling of Elevator Traffic Systems Using Queuing Theory

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Abstract. It has been long known that the elevator traffic system can be modelled as a multi-server queuing system. Each elevator can be represented as a server. The aim of this paper is to analyse the queue lengths and the average waiting times for elevator traffic systems using queuing theory.

A discrete event simulation queuing theory model for an elevator traffic system was built using the SimEvents blocks within Simulink. A large number of simulations were carried out on the SimEvents software to find the average passenger waiting time and the average passenger queue length for a simulation period length of 900 seconds.

It has been assumed that the passenger arrival process follows a Poisson distribution, and that the server inter-service time follows an exponential distribution (the average time taken to 'process' each passenger). A plot has been made of the average passenger waiting time and average passenger queue length against the system loading. The system loading is defined as the ratio of the actual arrival rate to the design arrival rate (λ divided by μ).

In order to verify the results from the queuing modelling, the average passenger waiting time and the average passenger queue length were also extracted from a MATLAB simulation model. Good agreement has been found between the two methods.

1 INTRODUCTION

Elevator traffic systems provide an ideal arena for the application of queuing theory. An elevator traffic system is a typical example of a queue-server system, whereby the passengers represent customers arriving for service, the lobby is a first in first out queue and the elevators represent a multi-server system. Applying queuing theory to elevator traffic system can be very insightful [2], and provides the designer with a 'macroscopic' view of the operation of the system and the inter-relationship between different performance parameters such as the queue length, the waiting time in the queue and the service time.

Queuing theory has been applied to elevators in order to assess the values of the waiting time and the queue length in the lobby. The most important piece of work that has been carried out in this area is that done by Alexandris *et al.* ([1], [4], [5], [6]). The work in [1] derives a set of equations that model the elevator system under up peak traffic conditions, in order to evaluate four parameters that are considered representative of the system performance. The four parameters are: average passenger waiting time in the main terminal (i.e. lobby); the average queue length of passengers waiting in the lobby; the percentage of busy elevator cars in the group; and the passengers delay time. In [4] formulae for the highest reversal floor in a round trip (*H*) and the average number of stops in a round trip (*S*) are presented, based on an assumed Poisson arrival process. The work assumes steady state operation, and thus assumes that the system manifests this performance continuously, once subjected to the specified level of passenger arrivals. There are two consequences to this critical assumption:

1. The elevator traffic system must be designed for an assumed infinitely continuous arrival rate, and must be able to infinitely sustain such an arrival rate without excessive queues forming and without excessive passenger waiting times.

2. The equation cannot deal with the case where the system is subjected to a passenger arrival rate that is sustained for a finite period of time (e.g., 5 minutes, 10 minutes; 15 minutes) whereby the arrival rate is equal to 100% of the design capacity (i.e., system loading is 100%) or even exceeds the system design capacity for short periods of time.

We, the authors of this paper, will attempt to use queuing theory and openly available software to explore the 'macroscopic' view of the performance of an elevator traffic system under finite workspaces (e.g., 5 minutes, 10 minutes, and 15 minutes) at system loading rates equal to or exceeding 100%. The motivation is that most elevator traffic simulation studies that are carried out today are usually run for finite period of time at system loading conditions of 100%. Moreover, it is useful in some case to assess the performance of a system when it is overloaded and subjected to system loading in excess of 100% (e.g., understanding the effect of the increase in a building population due to change of function; assessing an under-designed elevator traffic system).

As mentioned in [7], queuing theory modelling of elevator traffic systems allows a *macroscopic* view of the performance to be formed. It can be used to provide insights into the operation of the system and to allow general conclusions to be drawn. The elevator system details are ignored and the whole elevator system is treated as a black box that processes passengers.

Discrete event simulation software, SimEvents, which is part of Simulink/Matlab will be used in order to evaluate the passenger average waiting time and the average queue length in elevators. It is used to illustrate the effect of the workspace (i.e., simulation time) under the combined effect of the following two conditions:

1. Finite workspace (i.e., transient conditions as opposed to steady state conditions).
2. System loading values equal to or more than 100%.

Section 2 introduces the new concept of workspace that becomes indispensable once the assumption of steady state conditions has been abandoned. Section 3 introduces the equally critical concept of system loading, which becomes necessary once we assume the possibility of overloading the system above 100% of its capacity (as the term system utilisation becomes inappropriate). Section 4 introduces the SimEvents model used to run the simulations. Section 5 presents results from SimEvents and results from the Matlab code. Conclusions are drawn in section 6.

2   THE CONCEPT OF A WORKSPACE

A new term will be introduced in this paper, that of the *workspace*. A workspace is the period of time over which a variable is calculated (e.g., the round trip time) or the period of time over which a simulation is run. In classical design of elevator systems, it is customary to calculate the value of the round trip time over one round trip. In such cases, it can be assumed that the workspace is one round trip. In cases where the elevator system is simulated for finite periods of time, then the simulation will be equivalent to the workspace. It is for example customary to simulate the elevator system for a period of 5, 10 or 15 minutes (300, 600 or 900 seconds respectively). Passengers are generated for the duration of the simulation time, but the simulation continues until the last passenger has been *processed* (i.e., has arrived at his/her target floor and alighted). In queuing theory equation are derived that assume steady state conditions are achieved (e.g., Little's formula), which is equivalent to setting the workspace (i.e., simulation time) to infinity. As discussed earlier, work in [1], 4], [5] and [6] make such an assumption and derive steady state probabilities of the variables of interest. Three cases of workspace values are listed in Table 1 below.

Table 1: Various values of the workspace.

Case	The value of the workspace
Calculation of the round trip time	One round trip
Simulation (transient conditions)	The simulation time which is expected to be larger than the round trip time (e.g., 300 s, 600 s, 900 s)
Steady state conditions	Infinity

It is unusual in elevator traffic simulation to use long simulation workspaces that lead to steady state conditions, as this would lead to excessive queue lengths and excessive waiting, unless the system has been overdesigned in order to cope.

Once the concept of an infinite workspace has been abandoned, it is important to note that using different workspace values will lead to different results. For example using a workspace of 15 minutes would result in a longer passenger waiting time and a larger value for the average queue length compared to using a workspace of 5 minutes. *It is thus meaningless to enquire about the average passenger waiting time or the average queue length without specifying the workspace (i.e., the simulation time).*

3   SYSTEM LOADING

As discussed earlier, the system loading is an important concept in the design process. By varying the system loading, the designer can test the system performance. In cases where the design is using a finite workspace, the system loading can be set to exceed the capacity of the system for finite periods in time.

The corresponding term usually used in queuing theory is system utilisation. However, by definition, the system utilisation cannot exceed 100%, as it is meaningless to say that a server is occupied for more than 100% of the time. For these reasons, when attempting to subject the system to loading in excess of 100%, it is more appropriate to use the term system loading.

The emphasis on the arrival rate as an input to the system (in order to vary the system loading) is shown diagrammatically in Figure 1. The system has been designed for a passenger processing rate of μ passengers per second (or $c\mu$ in the case of multiple servers). The system is subjected to a passenger arrival rate of λ passengers per second. Once the system has been simulated for a period of time equal to the workspace (*WS*), the performance figures of average queue length and average waiting time can be extracted. By varying the value of λ above and below the value of μ, the system loading car set to value below and above 100%, respectively.
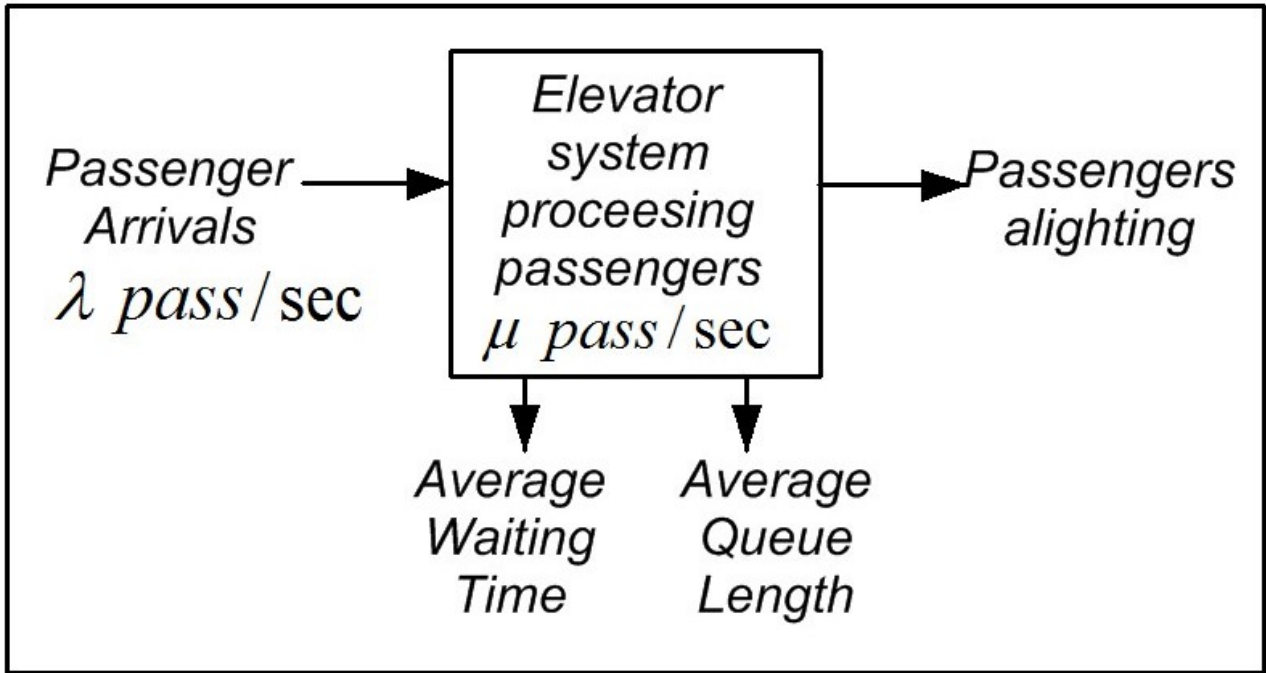
Figure 1: System loading diagram.

The general equation for system utilisation (or system loading as will be referred to in this paper) can be calculated as shown below:

$$\rho = \frac{\lambda}{c \cdot \mu}$$ ....(1)

Where:

λ is the passenger arrival rate in passengers per second

μ is each elevator's passenger processing rate in passengers per second

ρ is the system loading (dimensionless)

c is the number of servers in the system

But the number of servers in this case is equal to the number of elevators:

$$c = L$$ ....(2)

The inter-service time can be related to the elevator parameters as shown below (assuming bulk servers [3]):

$$\frac{1}{\mu} = \frac{\tau}{P_{max}}$$ ....(3)

Where

τ is the round trip time in seconds when it fills up with P_{max} passengers

P_{max} is the maximum number of passengers that can board the elevator car

μ is the passenger service rate for each elevator in passengers per second

Substituting (2) and (3) in (1) gives:

$$\rho = \frac{\lambda \cdot \tau}{L \cdot P_{max}} \qquad \qquad ....(4)$$

Noting that:

$$P = \frac{\lambda \cdot \tau}{L} \qquad \qquad ....(5)$$

Where

P is the average number of passengers boarding the elevator car

Then substituting (5) in (4) gives:

$$\rho = \frac{P}{P_{max}} \qquad \qquad ....(6)$$

...which is only valid for system loading values smaller than or equal to 100%.

This shows that the average car loading will in fact to equal to system loading. The work in [8] was based on a system loading evaluated as the ratio of the car loading. This was valid as the scope of the graph did not cover system loadings exceeding 100%. However, in cases where the system loading exceeds 100% loading, this measure becomes inadequate. It is then better to use the ratio of the arrival rate divided by effective service rate, shown in equation (7) below.

$$\rho = \frac{\lambda}{L \cdot \mu} \qquad \qquad ....(7)$$

4   THE USE OF SIMEVENTS

SimEvents is a graphical and modular discrete event simulation tool that is part of Matlab (specifically it is a toolbox within Simulink). It allows the user to build and simulate discrete event systems, and extract meaningful data about the performance of the system such as queue lengths, waiting times and system utilisation.

A simple example of a straightforward queue/server system is shown in Figure 2. It contains an entity generator (the term entity is the generic term used in SimEvents to represent customers/jobs/passengers....etc.); a First-In-First-Out queue; a multiple server system; and an entity sink (entities do not just disappear: they have to be disposed of somewhere).
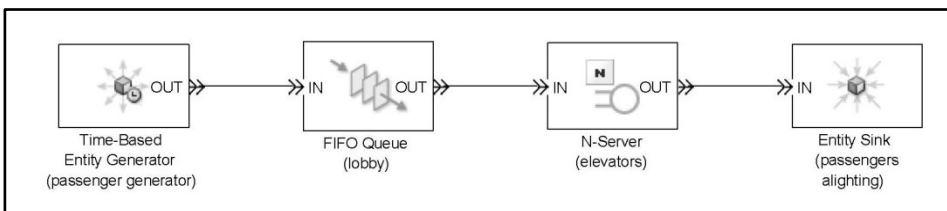
Figure 2: Simplified block diagram in SimEvents.

A more detailed model has been built in order to represent an elevator traffic system, operating in up-peak conditions, as shown in Figure 3. The model is a *M/M/c* model [10], whereby the arrival process has an exponentially distributed inter-arrival time, the server has an exponentially distributed inter-service time and there are *c* servers (i.e., elevators).

The model allows the workspace time to be varied whereby passengers will be generated for the duration of the workspace, and the servers are then allowed to continue processing any passengers remaining in the system.
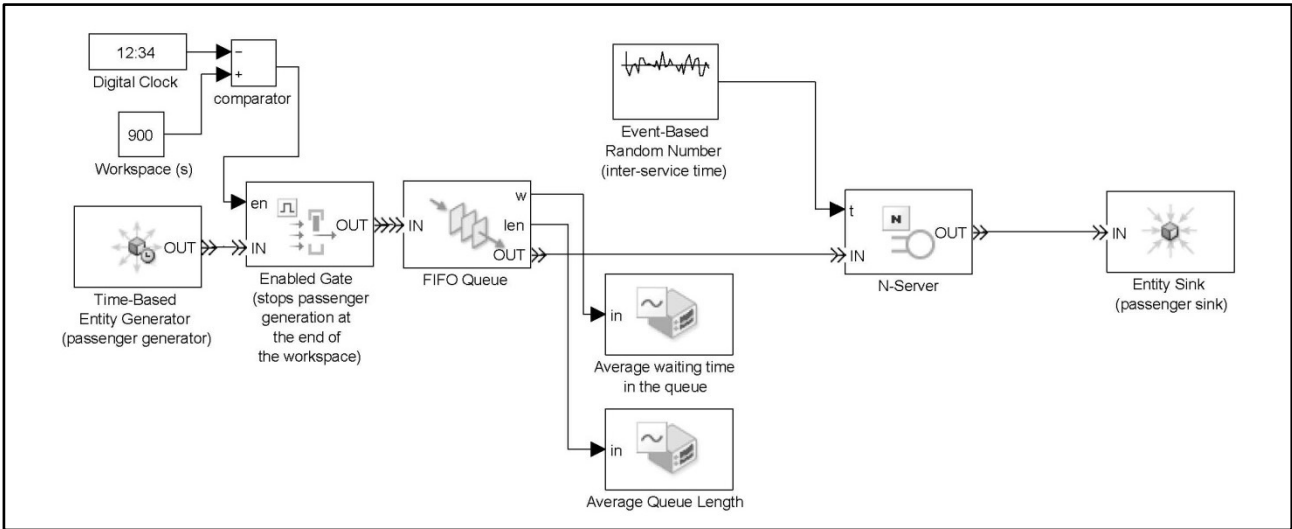
Figure 3: Detailed block diagram used in SimEvents in order to simulate the elevator system.

It is important to remember that nominal simulation time (the workspace) will be usually different from the actual simulation time. To illustrate such a difference, a queuing system has been simulated in SimEvents. The simulation time was set to 900 seconds. However, at the 900 second point, passengers were still present in the queue, as shown in Figure 4. The system continues processing the passengers until all have been processed through the server (i.e., elevators) and discharged, which takes place at the point in time of 985.6 s. Although the nominal simulation time is 900 seconds, the actual full simulation time is 985.6 s in order to allow the system to clear all the passengers waiting in the queue.
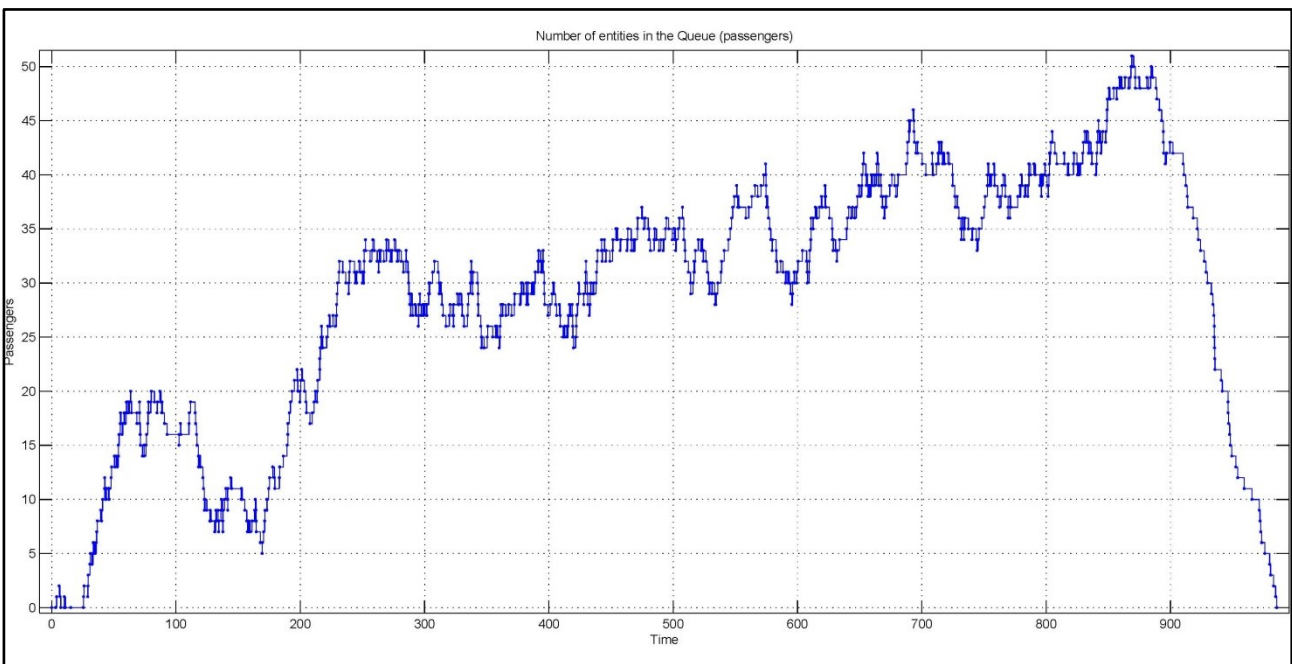
Figure 4: Number of passengers in the queue during the simulation.

5   RESULTS

In order to verify the results obtained from SimEvents, a Matlab code was written that also generated the average queue length and the average waiting time for passengers.

5.1   Effect of system loading on the AWT and the AQL

In the analysis below, system loading values have been varied from 0.1 to 2 (i.e., 10% to 200%). As the workspace in this case is finite (i.e., not steady state condition), the queue lengths and waiting times at system loading values of 100% will not be infinite, but will depend on the workspace duration. The results from the SimEvents package were compared to the results from the Matlab code and are shown in Figure 5 extracted from [8]. Good agreement can be seen in general.
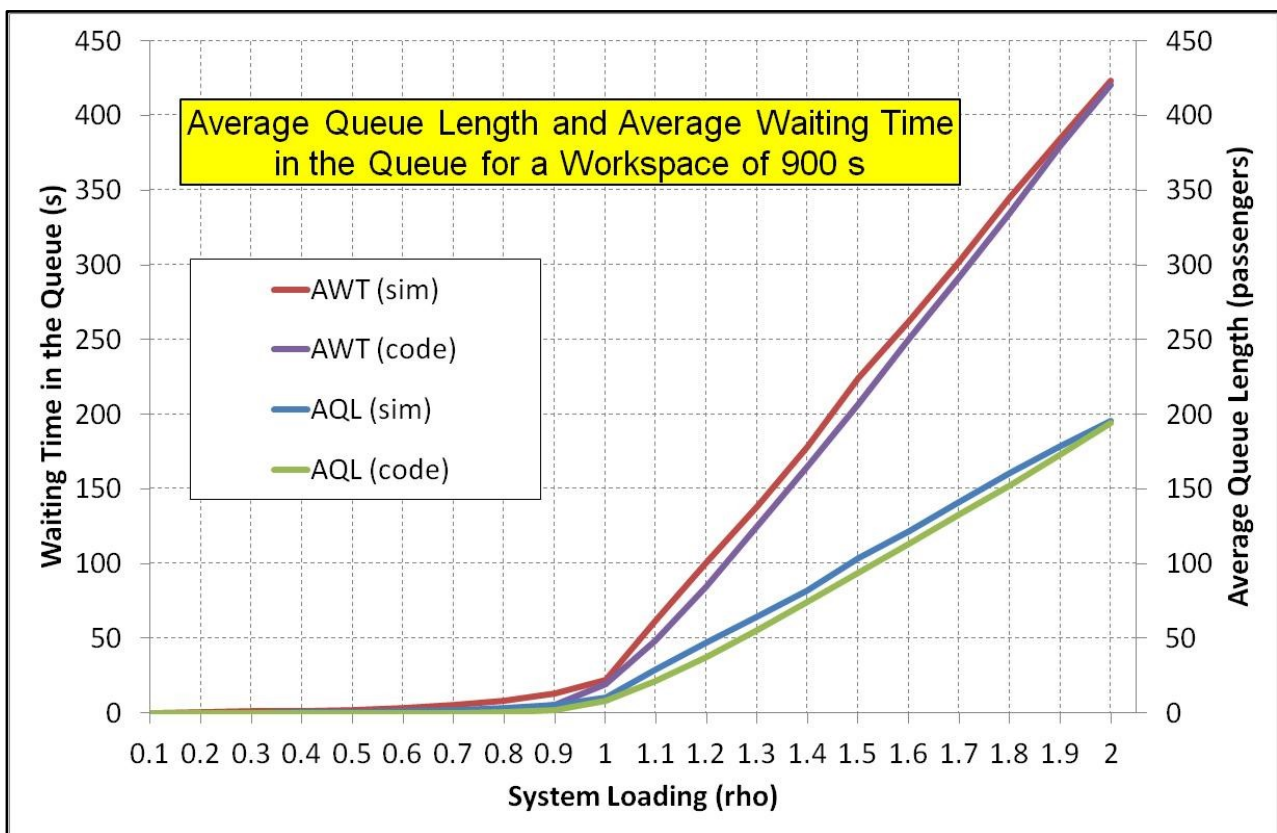
Figure 5: Comparison of the results from the SimEvents software and the Matlab code.

5.2   The effect of the workspace on the AWT and the AQL

The Matlab code was used in order to understand the effect of the workspace duration on the average waiting time and average queue length. Workspace values ranging from 300 seconds to 2700 seconds in steps of 300 seconds were used at a system loading of 100% (i.e., $\rho = 1$). In each case the average waiting time and the average queue length were recorded. As can be seen in Figure 6 the added trend-lines show that there is a near linear relationship between the system loading and the average waiting time and the average queue length, at a system loading of 100%.
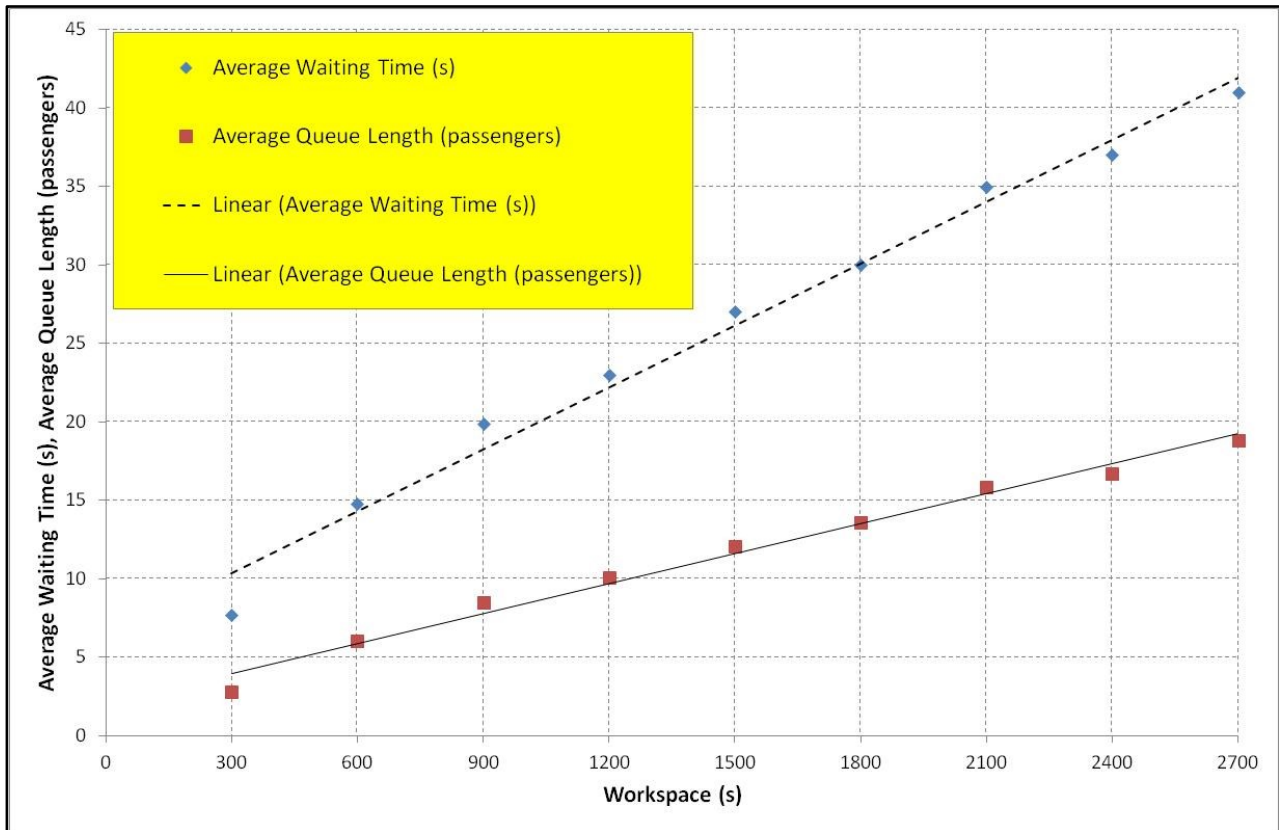
Figure 6:   The effect of the workspace on the average waiting time and the average queue length at 100% system loading ($\rho = 1$).

6   CONCLUSIONS

The concept of a workspace as used in elevator traffic simulation has been introduced. It is the length of time over which a variable is calculated or over which a simulation is run. The concept of a workspace is closely linked to elevator traffic simulation. Traditional queuing theory analysis assumes steady state conditions when deriving the equations for the average waiting time and the average queue length. The concept of a workspace however assumes finite running time and thus transient conditions. Such an assumption allows the designer to subject the elevator traffic system to system loading values in excess of 100%. This could represent real life conditions such as an increase in the population of a building, or an under-designed elevator traffic design.

A model in SimEvents has been developed that can be used to provide a macroscopic view of the operation of an elevator traffic system. It has been used to show the effect of system loading values in excess of 100% on the average waiting time of passengers and the average queue lengths. The results have also been compared to results from a Matlab code, and good agreement has been found.

The effect of the duration of the workspace was also investigated at system loading values of 100%. At 100% loading a conventional queue-server system under steady state conditions would be overloaded and waiting time and queue length would approach infinity. However, at finite values of the workspace, finite values of the waiting time and queue length will be attained. It was shown that there is a near linear relationship between the workspace duration, the average waiting time and the average queue length.

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BIOGRAPHICAL DETAILS

Lutfi Al-Sharif received his Ph.D. in lift traffic analysis in 1992 from the University of Manchester. He worked for 9 years for London Underground, London, United Kingdom in the area of lifts and escalators. In 2002, he formed Al-Sharif VTC Ltd, a vertical transportation consultancy based in London, United Kingdom. He has 17 published papers in peer reviewed journals the area of vertical transportation systems and is co-inventor of four patents. He is currently Associate Professor in the Department of Mechatronic Engineering at The University of Jordan, Amman, Jordan.

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The History of Lift Traffic Control[1]

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Keywords: Lift, traffic, control, collective control, sectoring, hall call allocation.

Abstract. The advent of FAPB (Fully Automatic Push Button) made the human operator or dispatcher redundant. Then the way lifts responded to passenger demands was in the imagination of "programmers" using relay logic and then programmers using digital computers. This paper looks at the history of the early relay based controllers and draws attention to their remarkable sophistication. These include: nearest car, fixed sectoring and dynamic sectoring. The ultimate traffic control, now used extensively and often inappropriately, is Hall Call Allocation. First described by G D Closs in 1970 (extending Leo Port's 1961 work), analysed by Sergio dos Santos in 1974 and implemented by Joris Schroeder in 1990.

1   THE REQUIREMENTS FOR THE TRAFFIC CONTROL OF LIFTS

The traffic control requirement is to co-ordinate a group of lifts to best serve passengers with the minimum of equipment.

2   SINGLE LIFT TRAFFIC CONTROL

2.1 Single Call Automatic Control

The simplest form of automatic lift control is single call automatic control. Single pushbuttons are provided on the landings and a button for each floor in the car. Car calls are given absolute preference over landing calls. If the lift is in use, a new landing call can only be registered, when the lift is no longer in use. This type of control is only suitable for short travel passenger lifts serving up to four floors, with a light traffic demand and is suitable for goods lifts.

2.2 Collective Control

The most common form of automatic control used for a single lift is collective control. This is a generic designation for those types of control where all landing and car calls made by pressing pushbuttons are registered and answered in strict floor sequence. The lift automatically stops at landings for which calls have been registered, following the floor order rather than the order in which the pushbuttons were pressed. Collective control can either be of the single button, or of the two pushbutton types.

2.3 Non-directional collective

Non-directive collective control provides a single pushbutton at each landing. This pushbutton is pressed by passengers to register a landing call irrespective of the desired direction of travel. Thus, a lift travelling upwards, for example, and detecting a landing call in its path stops to answer the call, although it may happen that the person waiting at the landing wishes to go down. This type of control is only acceptable for short travel lifts.

2.4 Down collective (up-distributive, down-collective)

Single pushbutton call registration systems may be adequate in buildings where there is traffic between the ground floor and the upper floors only and no interfloor traffic is expected, e.g.: car parks, public high rise housing, flats. Retaining the single pushbutton on the landing, a suitable control system is the down collective control (sometimes called up-distributive, down-collective)

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[1] © Gina Barney 2014

where all landing calls above the ground are understood to be down calls. A lift moving upwards only stops in response to car calls. A lift traveling downwards, answers car and landing calls in floor sequence.

2.5 Full collective (directional collective)

The two pushbutton full collective control provides each landing (except terminal landings) with one UP and one DOWN pushbutton and passengers press the pushbutton for the intended direction of travel. The lift stops to answer both landing calls and car calls in the direction of travel, and in floor sequence. This control system is suitable for single lifts or duplexes (two lifts) serving a few floors with some interfloor traffic. Typical examples are small office buildings, small hotels and blocks of flats. Directional collective control applied to a single lift car is also known as simplex control. The system can be applied to two or three interconnected lifts to work as a team, where a fully configured group control is not appropriate. Two lifts are termed a duplex and three lifts a triplex. Full directional collective control is the simplest form of group control.

3   GROUP TRAFFIC CONTROL

The purpose of group control is allocate landings calls in an optimal way to minimise: passenger waiting and journey times; system response time; energy consumption; maximise the handling capacity and reduce 'bunching'. These aims are sometimes in conflict.

4   LEGACY TRAFFIC CONTROL SYSTEMS

There were four basic (generic) types of traffic controller developed by the proprietary and independent manufacturers.

4.1 Nearest car

The simplest type of group control is the directional collective control described above. It is suitable for a group of two, or three lifts, each operating on the directional collective principles and serving seven or so floor levels. The controlled assignment of one lift only to a landing call can be achieved by the "nearest car" control algorithm.

The nearest car traffic control system is expected to space the lifts effectively around the building, in order to provide even service. The group traffic control feature contained in this simple algorithm is the allocation of each landing call to the lift that is considered to be the best placed to answer this particular call and no other. The search for the "nearest car" is continuously performed using quite sophisticated rules, until the call is cancelled after being serviced.

4.2 Fixed sectoring – common sector system

A fixed sectoring common sector control system can be devised for dealing with off peak traffic and can be complemented with special features to cater for heavy unbalanced traffic. The system divides a building zone into a number of static demand sectors equal to the number of lifts. A sector includes both the up and down landing calls at the floors within its limits. A lift is allocated to a sector if it is present in that sector and the sector is not committed to another lift. Fully loaded lifts are not considered for assignment. An assigned lift operates on the directional collective principle within the limits of its range of activity. The de-assignment of a lift from its sector takes place when the lift leaves the sector. A lift picks up calls ahead when travelling in either direction, even if it is not assigned to the sector.

The system, by distributing the lifts equally around the building, presents a good performance for uppeak and balanced interfloor traffic. It lacks a proper procedure to cater for sudden heavy demands at a particular floor.

4.3 Fixed sectoring – priority timed system

A fixed sectoring systems can also allocate the lifts on a priority timed basis. The landings in the building zone served by the group of lifts are grouped into independent up and down sectors. Each sector is timed as soon as a landing call is registered within its limits. The timing is measured in predefined periods of time, designated the priority levels. The system is unique among the classical traffic control systems as it considers time when making an assignment. The other algorithms only consider position. The assignment of lifts to the sectors takes into account the number and positions of the available lifts and the sector priority levels. The control system provides a good up peak performance and good down peak performance, especially under very heavy traffic conditions. The interfloor traffic performance is fair.

4.4 Dynamic sectoring system

The dynamic sectoring group supervisory control system provides a basic algorithm that groups landing calls into dynamic sectors. The position and direction of each lift defines the dynamic sector. Each lift answers the landing calls in the sector "ahead" of it. In parallel with the basic traffic algorithm, another dynamic sectoring algorithm is provided to insert free lifts ahead of lifts serving a large number of floors or a large number of calls registered in their dynamic sector. The dynamic sectoring system provides a very good performance for uppeak and interfloor traffic conditions, but a poor performance for down peak.

5   MODERN CONTROL TECHNIQUES

5.1   Fundamental Limitations

Although computer based traffic control systems can allocate lifts more efficiently than the relay based traffic control systems, there is a limit to what can be done. The main limit is the finite handling capacity resource of the underlying equipment to handle the traffic demands. This relies firstly on good equipment, which is properly set up and secondly on advanced control systems. Once the major inefficiencies have been removed such as: single button calling; stopping full cars; faulty detection of car loads; inefficient door operations; etc., then it is only possible to "trade" one parameter against another. This means that one passenger's shorter waiting time is another passenger's increased waiting time. The effect on the second passenger could be so small that it is unnoticed, but the effect on the first passenger could be significant.

The opportunity exists with a computer to program complex tasks to assist the landing (hall) call allocation process, which are impossible to achieve with fixed program systems. This might be considered to lead to truly optimal traffic control. An Estimated Time of Arrival (ETA) based traffic control system is an example, which allocates lifts to landing calls, based upon computed car journey times, ie: how long a lift takes to arrive. Early systems of this type, developed in the 1970s, substituted relay or solid state fixed logic by a truly programmable computer. This technique was an obvious one to use once programming facilities were available. The ETA technique remains the underlying basis of many computer based systems on the market today. A variation of ETA is estimated time to destination (ETD). This system not only estimates the time to arrive and pick up the intending passenger(s), but also the time to take them to their destination.

5.2   Stochastic Traffic Control Systems

Observations of classically controlled lift systems have indicated that the response times to answer landing calls follow a curved shape similar to the Exponential Distribution curve of Figure 1 (a). This distribution curve has a large number of calls answered in zero time or during the first time band. However, there is a long tail to the distribution with some calls waiting very long periods of time. Thus the underlying premise of algorithm design should be to bring the tail closer to the average and to sacrifice the "instant" collection of some calls by moving the exponential away from the origin to a Gaussian shape similar to the Rayleigh Distribution curve of Figure 1 (c).

(a) Exponential distribution

(b) Gamma distribution

(c) Rayleigh distribution

(d) Shifted gamma distribution ($a = 0.25$)
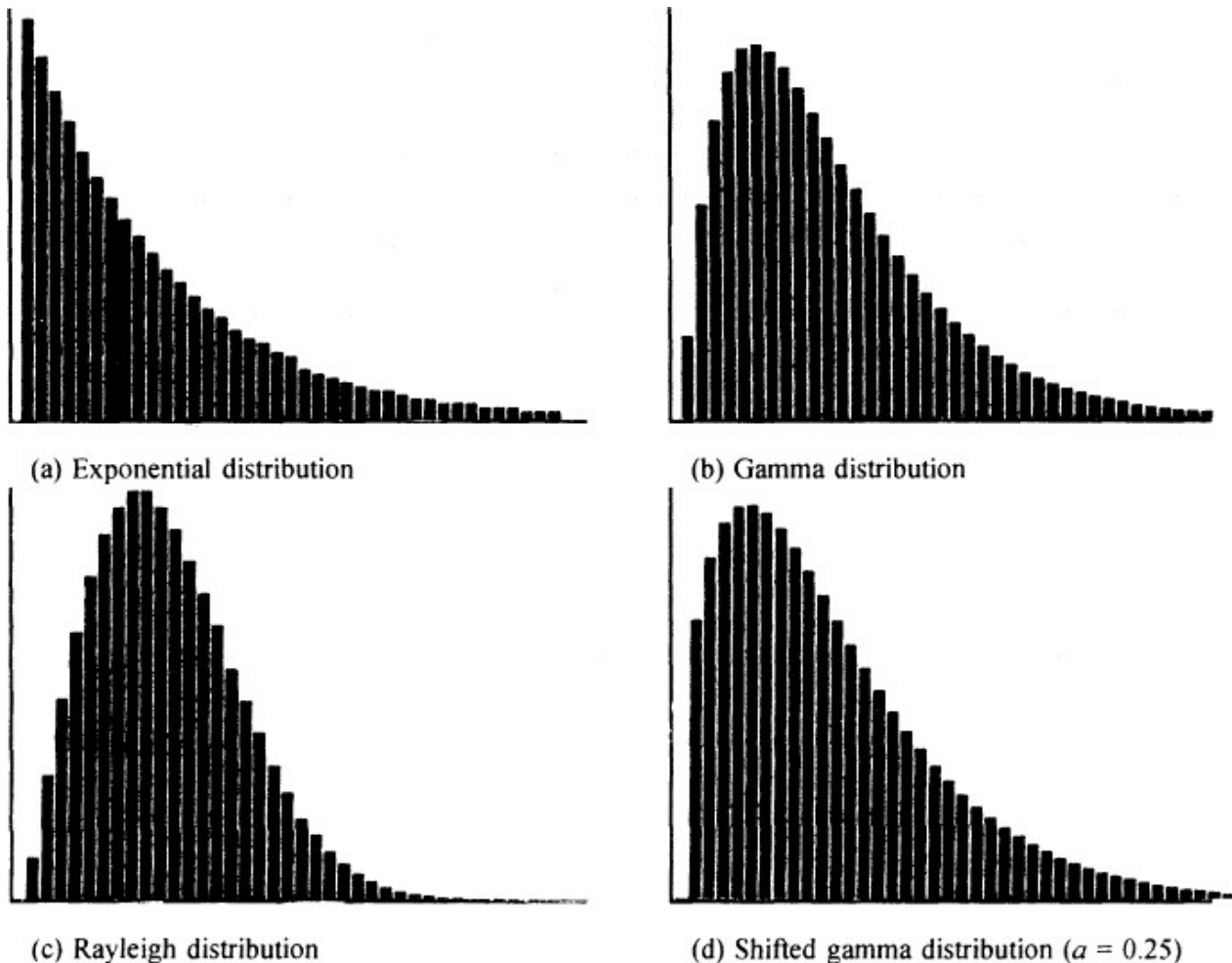
Figure 1 Statistical distributions (after Halpern, 1995)

Thus the stochastic control algorithm aims to provide an even service to all floors, where every landing call is given a fair consideration. This means that the landing call that has been waiting the longest should be given higher priority. The effect is to give a more consistent service to passengers; by trading the instant response calls to reduce long wait calls.

A stochastic[1] based traffic control system, named CGC was developed by Lim in 1983 and published (Barney and Dos Santos) in 1985 and implemented by at least one lift company (Godwin, 1986). It uses the principle that a landing (hall) call has to have waited a certain length of time before being considered for allocation (stops zero passenger wait times) and prioritises any call waiting over a high threshold time. The low and high thresholds are not fixed, but change to reflect demand by monitoring the average system response times.

What Lim proposed was subsequently analysed by Halpern (1992, 1993, 1995). Halpern showed that a classical traffic control system behaved as a Poisson process, but that computer based systems follow a shifted Gamma process, see Figure 1 (d). He also confirmed the premise of a finite (handling capacity) resource.

5.3   Hall Call Allocation[2]

5.3.1   Minimal Cost Functions

Calls are often allocated to a suitable lift using the concept of minimum cost, ie: a cost function[3]. This concept operates by performing a trial allocation to all available cars and allocating the call to

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[1] The term "stochastic based", meaning "aim at a mark, guess".

[2] The term destination control, which is sometimes used is misleading. A lift traffic control system can only allocate a passenger's hall call to a suitable car, ie: Hall Call Allocation. The system cannot control the passenger's destination: that option belongs solely to the passenger.

the car presenting the lowest cost. There are criteria for selecting a suitable cost function. These can, for example, be based on either Quantity of Service, or Quality of Service, or both. In general terms, the Quantity of Service is a measure of the lift capacity consumed to serve a specific set of calls, indicated by the total of the journey times of all the cars. This could be minimised by keeping passengers waiting in a lobby until there were enough passengers to make a trip worthwhile. Airlines apply this principle. The Quality of Service is indicated by the average value of either the passenger waiting time or the passenger journey time (waiting time plus in-car travel time).

The minimisation of waiting time implies putting passengers into the first lift that arrives. This would result in no change from the usual procedure. The minimisation of the total car travel time implies using the smallest system capacity, which is equivalent to using the smallest possible number of cars. The result of this policy would be very large passenger waiting times, a result which would not be acceptable. This criterion alone is thus not suitable as a cost function. The minimisation of average passenger journey and waiting times are more acceptable objectives. Both times are interrelated and the minimisation of one might be achieved at the expense of the other. An accurate calculation of passenger journey time can only be achieved if passenger destinations are known at landing call registration time.

5.3.2 A new signalling system

The idea of destination buttons on the landing was first proposed by Leo Port (1961, 1968), but he only had relay logic in which to implement it and could not provide dynamic allocation, only fixed allocation. Installed in two buildings in Australia it functioned in one for some 20 years or more. A dynamic (ACA) system was first described by Closs in 1970, detailed by Barney & dos Santos in 1977 and partially implemented by a major lift company in 1990 (Schroeder, 1990c), when computer technology had caught up with the ideas. Now installed in many buildings, it has gained acceptance across the world as efficient. Most manufacturers have now applied the technique – some very badly.

Hall call allocation gives the opportunity to track every passenger through from registration to destination. This has great advantages during uppeak as passengers can be grouped to common destinations, as there are larger numbers of them. The individual waiting time may increase, the travel time may decrease, but there would be an overall reduction in journey time. During down peak there is no advantage as the destination floor is known. During reasonable levels of balanced interfloor traffic there is little advantage as most landing (hall) calls and car calls are not co-incident and car loading maybe one or two persons. However, during an uppeak with some down travelling traffic, or a down peak with some up travelling traffic, there are benefits. This leads to a conclusion that an optimum cost (money) system would have a full call registration station at the lobby and other principal floors and two button stations at all other floors. The control algorithm can go into "simple" mode, when dealing with the two button stations by knowing the direction and guessing the destination.

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INTERLUDE

As so few people understand Hall Call Allocation and its derivative Adaptive Call Allocation, including most manufacturers it is worth an interlude to explain the basics.

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I – 1 The simple cost function

During an uppeak, the obvious cost function to implement with call allocation is journey time. This is because a waiting time allocation criterion would do no more than allocate every new call to the first available lift at the main terminal which possessed space capacity, in the same way as the collective-distributive algorithm. If journey time is the cost function, calls terminating at the same

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[3] "Cost function" is optimal control theory terminology and its equivalent inverse, the "performance index", is sometimes quoted. Its converse is a "penalty function".

floor tend to be allocated to the same lift, hence reducing the number of stops per trip and the round trip time. The system handling capacity is increased and the main terminal floor more frequently served. However, a waiting passenger may not be allocated to board the first available lift, and this may produce increased waiting times. The overall effect is that better journey times are produced, in comparison to conventional algorithms, for the whole range of traffic intensities, but can result in longer waiting times. It is better to sacrifice some passenger waiting time and use passenger average journey time as the cost function. The maths is as follows.

Consider that a new call is to be allocated to a system of *L* lifts, each lift (*I*) with *N(I)* calls to answer and *JT(I)* accumulated journey time for the *N(I)* calls.

Assume that *NJT(K)* is the new accumulated journey time for *N(K) + 1* calls, when the new call is allocated to lift *K*. The average journey time for the complete set of calls is:

$$AJT = \frac{NJT(K) + \sum_{I=1, I \neq K}^{L} JT(I)}{1 + \sum_{I=1}^{L} N(I)} \tag{1}$$

This can be written as:

$$AJT = \frac{NJT(K) - JT(K)}{1 + \sum_{I=1}^{L} N(I)} + \frac{\sum_{I=1}^{L} JT(I)}{1 + \sum_{I=1}^{L} N(I)} \tag{2}$$

As the two summations in Equation (2) do not depend on the allocation *K*, the minimisation of *AWT* only requires the minimisation of the term *NJT(K) - JT(K)*. This simplifies the evaluation of the cost function, as only this incremental cost is to be evaluated instead of the whole expression for *AWT*. The quantities *NJT(K)* and *JT(K)* are evaluated by simulation.

It should be noted that the incremental cost *NJT(K) – JT(K)* is made up of several terms. It includes the waiting and journey times for the new call and the increase in the waiting and journey times of calls already allocated to lift *K*, the extra passenger transfer time resulting from the new call, and any extra stops to pick up and discharge the new passenger.

I – 2 Average Journey Time with Maximum Waiting Time Constraint

A third type of cost function, proposed by Closs (1970), uses average journey time with a maximum waiting time constraint. It operates by costing each allocation against an average journey time cost function, but penalising any solution for which the waiting time of the new call exceeds a predefined value of maximum wait (*MWT*). The Adaptive Call Allocation algorithm operates as follows:

(1) Evaluate cost of allocation of the new landing (hall) call to lift 1:

$$COST(1) = NJT(1) - JT(1) \tag{3}$$

(2) Compare the new call waiting time *NCWT(1)* with the predefined value *MWT*. If it is smaller than *MWT*, then *COST(1)* is not altered, but if it is greater a penalty is added to the cost:

$$COST(1) = COST(1) + \text{penalty} \tag{4}$$

The penalty is made up of a fixed value added to a term proportional to the excess of waiting time above *MWT*. For example:

$$\text{penalty} = 300 + 10 \ (NCWT(1) - MWT) \tag{5}$$

(3)   Repeat the procedure from (1) for all lifts.

The effect of using a penalty is to force the elimination of the allocation to lifts with an existing high number of allocations from receiving another allocation, making it easier to select a more lightly loaded lift.

I – 3 Reduction in Number of Stops

The "positive" concept of using a cost function as a performance index can be transposed into a "negative" concept of penalty functions in order to promote higher efficiency. An example of a penalty function is the rejection of an allocation which introduces an additional stop.

The call allocation algorithm causes calls requesting the same destination floors to be carried by the same lift. This has the effect of reducing the number of stops. However, in some cases the cost of allocating a new landing (hall) call to a lift already stopping at the calling landing (hall) or destination floor is marginally greater than the cost to allocate the call to another lift not stopping at either floor. Although the allocation is perfectly proper, it might be better not to allocate the new call to the lift with the lowest cost, as by not doing so capacity is reserved for future calls. To cater for this idea a penalty $p\%$ is introduced for each extra stop motivated by the new call. To prevent operation of this penalty under low traffic conditions, the penalty is made dependent on the incremental cost of the allocation and is proportional to car load.

$$\text{penalty} = \frac{p}{100} \times \text{incremental cost} \times \frac{\text{load}}{AC} \qquad (6)$$

where, AC is the actual car capacity and the load is measured as the average value of the number of passengers inside the lift, or queuing for service. The procedure improves performance for values of p up to 10%. For larger values of p the algorithm is self-defeating, as it produces less appropriate allocations.

I – 4 Dynamic Uppeak Sub-zoning

Uppeak sub-zoning is sometimes used by conventional group control systems to improve the uppeak handling capacity. Sub-zoning is very sensitive to where the zone partition is fixed and should ideally be adjusted for every traffic situation. As in practice a fixed partition is implemented, it cannot respond to the wide fluctuations found in arrival traffic patterns. Knowing the advantages of uppeak sub-zoning, and the adaptability of a computer implemented algorithm in coping with input traffic variations, a dynamic sub-zoning concept can be implemented in the ACA system. The building is divided into three sub-zones, as shown in the figure.

| upper subzone |
| median subzone |
| lower subzone |
| main terminal |
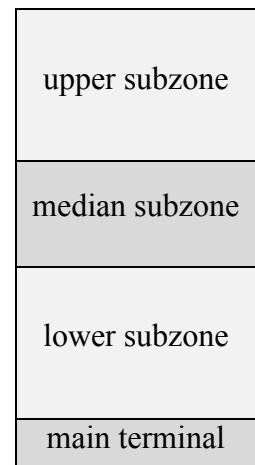
The lifts are divided into two subgroups, one for the lower sector and the other for the upper sector. No indication of this partition is given to the passengers. A newly registered landing (hall) call is allocated to a lift in the usual way, by evaluating the costs of the allocation of the call to every lift and choosing the allocation giving the lowest cost. However, during the evaluation of the cost, the allocation of a call registered for the lower subzone to a lift allocated to the upper subzone is penalised, and so is the allocation of a call with a destination in the upper subzone to a lift in the subgroup serving the lower subzone. The penalty, which is added to the cost of the allocation, is a function of the load of the two subgroups of lifts, and can be expressed as:

$$\text{penalty} = \left(1 + \frac{b}{100}\right) M \qquad (7)$$

where, M is a constant value and b measures the imbalance of lift loads between the upper and lower subgroups as a percentage of the highest subgroup lift load.

The fact that the loads of the two subgroups of lifts are taken into account contributes to equalise these loads. For example, the allocation of a call terminating at a floor in the lower subzone to a lift assigned to the upper subzone can be penalised by a quantity ranging from zero, if all the upper subzone lifts are idle, to $2M$, if the lower subzone lifts are idle.

A call registered to the median subzone can be allocated to either subgroup of lifts, with preference for the subgroup with the smallest load. The allocations to the lifts assigned to the heavier loaded sub-group are penalised by a quantity which equals the absolute value of b multiplied by M.

A correction mechanism allows this technique to deal with extremely unbalanced traffic destinations, as if excessive unbalance between the subgroup loads is detected, the subzone limits are automatically adjusted.

I – 5 Walking time

A further feature is necessary in the call allocation control algorithm. After registering the required destination floor and receiving a reply as to which lift will service the landing (hall) call, a passenger must walk to the lift. Thus, the allocation procedure must allow sufficient walking time for the passenger to reach the lift from the landing (hall) call station when allocating the landing (hall) call to a lift.

I – 6 Look ahead (*K*)

Although the mathematics suggest hall call allocations to up to *K* lifts (see equations (1) and (2)), in practice a "look ahead" (*K*) of from 2 to 4 only is practical. This also implies groups of six or more cars.

~O~O~O~

5.3.3 Conclusions on Modern Traffic Control Techniques

There are a number of other techniques, which can be applied to the conventional two button and hall call signalling systems. These include: expert systems (Qun et al., 2001); fuzzy logic (Ho and Robertson, 1994); dynamic programming (Chan and So, 1996); genetic algorithms (Siikonen et al., 2001; Miravete, 1999); knowledge based systems (Prowse et al., 1992); neural networks (Barney and Imrak, 2001) and optimal control (Closs, 1970). Many of the advanced control techniques employ complex mathematics and involved programming, which makes the practical implementation of the traffic controllers difficult. Also the proper understanding and correct adjustment on site by installation and service persons is doubtful and there is also an increased risk of system unreliability. Powell (2001) states "… *the added complexity involved in creating these (neural) networks and putting them into production could not be justified on the (slightly) expected gains in dispatching performance ... over less complicated techniques*".

The use of any of the techniques during a dominant traffic flow, such as uppeak or down peak, is unlikely to improve traffic handling over a minimum cost algorithm. The provision of additional destination information, as with call allocation, is unnecessary during light traffic conditions, ie: balanced interfloor, and becomes most effective for heavy traffic situations, particularly uppeak. Then passengers for common destinations can be assembled to travel together. The technique improves the handling capacity for uppeak, but does not assist down peak or interfloor traffic handling (Barney 2000a, 2000b).

Once a computer is employed to implement the control strategy, the final algorithm is limited only by the imagination and ability of the program designer. For example, the search for a "bumpless" transfer of control strategy can be dealt with by having one algorithm able to adapt to changing traffic conditions. Also the Hall Call Allocation algorithm becomes the Adaptive Call Allocation by detecting when to switch from a waiting time to a journey time cost function. The stochastic algorithm CGC could easily be married to the Hall Call Allocation to restrict the allocation of landing calls to those that have been waiting for a threshold period of time. Learning algorithms can be added to "predict" outcomes and learn to improve the calculation processes such the estimated time to reach a landing (hall) call.

All these techniques allow the use of the underlying resource (handling capacity) more effectively for the benefit of all passengers. An added advantage is the systems become more consistent in their response to passenger demands.

6   COMPARISIONS

Readers are invited to examine Figure 2. The three main (pure) traffic demands are shown. Note how no one algorithm works for all three.

LEGEND COL = Collective, DSF = Dynamic sectoring with sub-zoning,
FSO = Fixed up/down sectoring, FS4 = Fixed sectoring, priority timed,
HCA = Hall Call Allocation, ACA = Adaptive Call Allocation
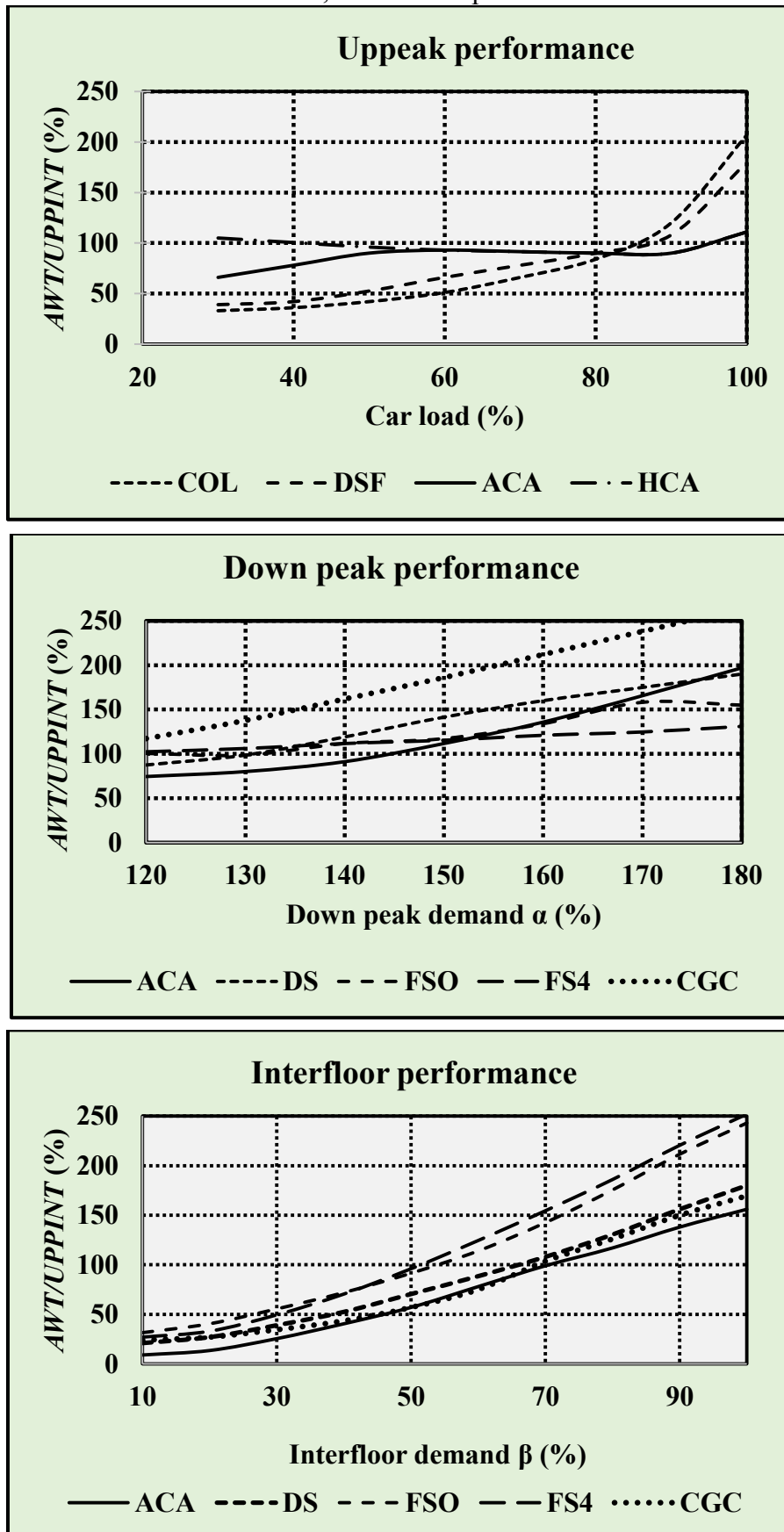
Figure 2 Comparison of traffic control algorithms for three traffic demands

ACKNOWLEDGEMENTS

This author acknowledges the work of her team at the University of Manchester. She started to study lift traffic control and design in January 1968, after she had graduated with an MSc in control theory (1962) and a PhD in control practice (1965). The principal members of her team included: David Closs, who researched simplex control (1968) and then analysed hall call allocation in 1970, Sergio dos Santos, who wrote an interactive lift simulation "app" known as LSD in 1972 and analysed several control algorithms in1974, Bill Swindles, who programmed up many of the algorithms in 1975. Other postgraduates included: Mahommed Moussalati (1974), Saideh Hirbod (1975), Nick Alexandris (1977), Jonathan Beebe (1980), Sinha Lim (1983), Lutfi Al-Sharif (1992), Erdem Imrak (2001). There were at least a score of undergraduates who also contributed.

WHERE CAN FURTHER INFORMATION BE FOUND?

As time passes the brain's neurons cease to connect and this author forgets. Fortunately anyone wishing the study lift traffic control in depth can do so as the author wrote it all down before she forgot. If anyone is seriously studying traffic control then they will already have two books Elevator Traffic Analysis Design & Control (1985) and the Elevator Traffic Handbook (2003). All the references referred in this paper are there. New researchers are directed to: Chapter 3 of Lift Traffic Analysis, Design and Control, Barney and dos Santos, 1/ed, 1977for legacy systems and a comprehensive description of Hall Call Allocation. Section 7.2 of Elevator (*sic*) Traffic Analysis, Design and Control, Barney and dos Santos,2/ed, 1985 for computer group control. And Pages 245–302 of Elevator (*sic*) Traffic Handbook, Barney, 2003.

BIOGRAPHICAL DETAILS

Dr Gina Barney, PhD, MSc, BSc, CEng, FIEE, HonFCIBSE is an independent vertical transportation consultant, working with the lift industry since 1968. She is an author, co-author and editor of over 120 papers and books.

Modernising a Paternoster

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Abstract. This paper describes the processes involved in modernising a fifty year old paternoster in a grade 2 listed, University building with 22 occupied floors. The contribution of the paternoster to the vertical transportation of the building is assessed. Key components of a paternoster lift are described and the operation of the device is explained. The accident history of the device is detailed and the design features to reduce risk are explained and reference is made to a recent fatality on a paternoster in the Netherlands. Unforeseen difficulties during the construction phase are discussed and the solutions adopted are demonstrated. The project is reviewed and its success is considered. The paper concludes that without a working paternoster the Arts Tower Building could not accommodate its current population.

1.   INTRODUCTION

An early form of Paternoster was installed at Oriel Chambers in Liverpool in 1868 [1] and thought to be designed by its Architect Peter Ellis. Subsequently the paternoster was "invented" and built in 1884 by the Dartford, England, engineering firm of J & E Hall and was known as the Cyclic Elevator [2]. The name paternoster ("Our Father", the first two words of the Lord's Prayer in Latin) was originally applied to the device because the paternoster cars travel in a loop and are thus similar to rosary beads used as an aid in reciting prayers.

Paternosters were popular throughout the first half of the 20th century as they could transport more passengers per given floor area than ordinary lifts. They were more common in continental Europe, especially in public buildings, than in the United Kingdom. They are rather slow typically travelling at about 0.3 or 0.4 meters per second, thus allowing a passenger transfer time of about 1.5 seconds within a safe transfer zone.

The Arts Tower at the University of Sheffield is a grade 2 listed building. The scope of its listing covers internal as well as external features. It was built between 1961 and 1965 and designed by Gollins, Melvin,Ward & Partners with 22 occupied floors and 78 metres rise. The design population was 1740 and vertical transportation was provided by 2 conventional 1250Kg lifts and a paternoster with 38 cars. There are only two small stairwells serving all the floors in the building. The lower ground floors and mezzanine floors have additional stairs to cope with the peak passenger transfer to the large lecture theatres on the lower ground floor and the adjacent library accessed via the mezzanine.

The lifts and paternoster were originally installed by Schindler in 1964 and were operational at the official opening of the building by Queen Elizabeth the Queen Mother in 1966.

Following a fatal accident in Newcastle in 1970 all paternosters were modified to include a car stability tracking system to help prevent a car pile-up when reversing direction of travel between the up shaft and down shaft. In 1995 D&A lifts modernised the lifts and paternoster. A further more detailed modernisation was carried out between 2009 and 2011 by Stannah lift services (lifts) and Industrial Marine Lift Services (paternoster).
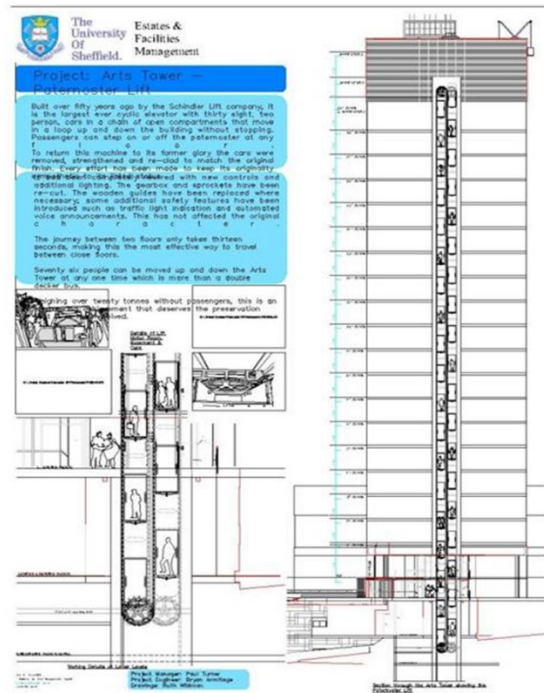
Figure 1 The University of Sheffield Paternoster display board.

2.   STANDARDS APPLICABLE TO PATERNOSTER MODERNISATION

It is a source of irony that most Paternosters in the UK were installed prior to the publication of BS2655 part 5 1970 [6]. This part of an old British Standard specifies engineering and safety requirements for paternosters and though withdrawn the standard remains the only specific reference source currently available for paternosters. BS 5655 part 11[7] suggests itself as a source of recommendations for the modernisation process. BSEN81 part 80[8] suggests itself as a reference for the modernisation process. Unfortunately the communality of components between lifts and paternosters is much less than might be anticipated and so these lift specific standards are of some limited guidance to a paternoster modernisation designer. Some fundamental principles however can be readily adopted from these standards:-

1) "Do no harm" always make the modernised device safer than the original.
2) Assess risks and research safety records to focus on problem areas.

The essential health and safety requirements of the Supply of Machinery Regulations [9] would apply to new paternosters but existing paternosters are not subject to those requirements and similarly problems exist in defining legal references in LOLER [4] and PUWER [5].

2.1   Paternosters and the law

There is a common misconception that the use of a Paternoster is illegal. LOLER regulation 47a [4] refers to paternosters and allows for the absence of car doors and limits the practicality of edge protection to safety handles and landing barriers (for when the machine is stopped). Several sources state that new Paternosters cannot be installed and though legal restrictions do not seem to be in place the real issue is that few manufacturers would be prepared to design and CE mark such a product today.

2.2   Paternosters and suitable users

Children may not appreciate the risks presented by paternoster travel and may try to lift flaps and come into contact with other objects. Disabled, infirm or intoxicated passengers are much more at risk of injury on a paternoster. The use of Paternosters by the elderly is problematic as there are several features of aging which increase the difficulties that paternosters present. Reaction times slow down with age. The ability to balance on one foot on a moving object and simultaneously transfer body weight from one foot to the other decreases with age and level of fitness. All users become more competent with practise and accidents with experienced users are rare.

All these comments could of course apply equally to escalator usage. It may be politically incorrect to state (but it is never the less true) that suitable paternoster passengers should be fit and able bodied aged between 18 and 70. This demographic describes over 95% of a typical University campus.

2.3   Paternosters and the movement of goods

Paternosters must not be used to transport goods. There have been many accidents involving ladders or boxes getting trapped between a landing floor and a car ceiling or a car floor and a landing header. The simple chord protection over each landing entrance cannot ensure safety. Even carrying a heavy or large briefcase can increase risks.

2.4   Why modernise a paternoster?

If there is no established standard to work to and normal edge protection measures are impractical it may be prudent to consider why modernise a paternoster at all? This paper refers to the modernisation of The Arts Tower Paternoster and application of any learning outcomes from this paper should be tempered by the design constraints applicable to this Grade 2 listed building. The real question that is being answered is why paternoster was modernised.

If the Paternoster was not to be kept in use due to its listing it would have to have been left as a static display and hence the area of the paternoster shafts would have been lost. The small foot print of the building and the internal listing requirements meant that increasing the size of existing lifts or adding more lifts to the group was impossible. A traffic survey was carried out in March 2008 and found that the paternoster transported up to 60 persons in an up peak 5 minute period whereas the lifts only managed to transport 40 persons. If the Arts Tower were to survive as a working academic building then without the paternoster the population above the mezzanine floor would have to be reduced by up to 60%. At the time of the survey the University were in contract with a Main Contractor who was starting a £70 million project to modernise the building over a three year period. Just as the University was about to embark on the paternoster project their external consultant who had run the previous modernisation project reported some very bad news. The load chains and main drive gearing were inspected by a "specialist" and declared unsafe due to wear in the gearing and support bearings and stretch on the load chains. The machine which had become very noisy, was taken out of service as a precaution by the University. Prior to receiving the traffic survey report the modernisation had been put on hold. Given the report's conclusions this was not a viable option.

2.5   The Modernisation of the Arts Tower Paternoster

Lerch Bates were appointed by the University of Sheffield to run the Paternoster Modernisation in 2009 after their own research led them to conclude they needed another source of advice. Three independent surveys of the chain condition concluded that the chains were suitable for use for the foreseeable future as only superficial chain link extension was measured after 53 years operation. The first problem for the Consultant to address was to identify suitable potential candidates for the paternoster modernisation. The starting point was the manufacturer, existing maintenance contractor

and the University lift modernisation approved list. A series of meetings was held with potential contractors so that the nature and scope of the works could be explained ahead of invitations for an expression of interest for the contract. Eventually six contractors returned an expression of interest. An analysis of the safety reports was completed on the paternoster since the last modernisation and risk assessments were carried out in order to produce the modernisation specification.

2.6   Development of the Modernisation specification

The University of Sheffield's Estates department had access to the safety records of incidents relating to the Paternoster. These records reached back to the time of the previous modernisation. The incidents fell into three clear categories:-

1) Incidents involving trapped goods (ladders in several cases)
2) Incidents involving trapping between fixed and moving handrails
3) Falls from the paternoster cars (2 incidents both involved intoxicated passengers).

A risk assessment using the format of ISO TS14798 2006 was carried out and identified deficiencies in design and deviations from BS2655 Part 5. Certain changes were proposed some of which the University and or English Heritage would not accept and hence the specification did not include the following items:-

a) Provision of a large computer display at ground floor showing a video giving user instructions for the safe use of the paternoster. Fixed notices following BS2655 Part 5 were retained.
b) Infra-red passenger detectors in place of the chord switches above each landing entrance. The University did allow these but on the top entrance only retaining the chord switches on other landings.
c) No method of preventing falls from the paternoster cars was adopted as any method considered that prevented a fall increased another type of risk. There had only been 2 falls in the last 15 years and in both cases the students involved were found to be under the influence of alcohol. The Handrails and car flap signage required by BS2655 Part 5 help reduce the likely hood of falls to an acceptable level. The handrails were modified to reduce the risk of trapping.

A summary of the specification requirements is found in Annex 1.

2.7   Project progress

The job was tendered in the summer of 2009 and five compliant tenders were received. The successful tenderer was Industrial Marine Lift services of Heywood Greater Manchester. Industrial Marine (as their name implies) specialise in lift and escalator repairs and modernisations on ships. The nature of their work relies on the high level of engineering skills of their fitters and their ability to problem solve in a challenging environment.

Site work began in 2010 by erecting full height hoardings over each entrance, removing the paternoster cars and scaffolding the paternoster shafts. A long period of degreasing and cleaning all the shafts steel work and components was followed by sealing and repainting. The cars were stored on University premises about half a mile from site and the intention was to refurbish the cars during the period whilst the gearing was removed to Highfield Gears of Huddersfield who were chosen to replace the machine components. During this period two separate events changed the course of the project and left new unexpected challenges.

Asbestos was discovered in the sub-basement of the Arts Tower and this effectively meant that the paternoster shafts which enter into the sub-basement had to be sealed and no access to the pit was possible until the material was removed. This led to a six month delay in site works.

Meanwhile an inspection of 30 of the 38 paternoster car slings after cleaning and sand blasting showed signs of structural failure. In most other places in the world this would have been a show stopper. Here at the University of Sheffield however there is the Sheffield University Metals Advisory Centre (SUMAC) based just across the road. Adrian Taylor a senior consultant for SUMAC was engaged and one of the faulty slings was fitted with strain gauges. The car was refitted in the paternoster shaft and the strain gauge reading were recorded. The results were analysed and a suitable structural modification to the gearing alignment and each car was identified. Interestingly the car bracing was a modification of the additional bracing that Schindler had retrofitted in the 1970's. The new gearing was installed and then correctly aligned by Highfield Gears Engineers. The modified car was sent on another series of test runs with the stain gauges and the results were shown to be within acceptable elastic limits. The problem was resolved and maintenance checks were refined to include ongoing monitoring of the issue.

Once the asbestos was removed and air tests proved negative the major site works began in earnest in Jan 2011.

During the course of the works English Heritage carried out a series of surveillance visits and were satisfied with the appearance of the refurbished cars which were significantly lighter than before despite being clad in stainless steel rather than aluminium with an additional MDF lining. They were also happy with the redesigned car and landing handrails. The original handrails created a pinch point between the static landing handrails and the moving car handrails. The redesigned ramped surfaces deflected limbs rather than trapping them. This had previously been cause of injury on 2 occasions.

To assist passengers time their entry and exit the existing listed landing floor legends were back lit with colour LED's. The indicators were illuminated red at all times a lift car floor was not within + or – 200mm of a landing level and illuminated green when a car is within that zone.

The existing motorised brake was replaced with a brake compliant to EN81-1. The drive control was changed from star delta to VVVF and the control system was designed by ILE Controls of Leicester to include a comprehensive diagnostic system and a more accurate car stability tracking monitor.

By August 2011 the Arts Tower Building modernisation project was nearing completion and the paternoster program had to be accelerated to meet the start of the new term on 21/9/2011. Extensive safety checks were carried out on all the new and retained equipment and on 20/9/2011 the refurbished paternoster was ready to put in to service.

3   COMPLETION A WELCOME RETURN TO AN OLD FRIEND?

During fresher's week the new students showed less enthusiasm for the newly modernised paternoster than expected. There were a few teething problems and a contractor trapping a ladder in the roof of a car in the first week was not welcome news. When the rest of the students returned to the newly refurbished building the reaction was much more positive. Over the next few months the machine operation as a whole had become smoother and quieter in operation and now three years on the ride is very satisfactory. The use of the building had been revised and in place of seminar rooms, Administration offices, Human Resources and the Estates Department were deployed in to the building. This reduced both the population above mezzanine and the volume of passengers due to the hourly changeover of students in lectures and seminars. The newly refurbished lifts had the advantage of direct into floor approach, fast acceleration and door times which improved lift performance. The VT service to the building was significantly improved but the paternoster still transported the majority of passengers.

3.1   A worrying post script

In November 2013 Dr Richard Peters received an email concerning a fatality on a Paternoster in the Netherlands. Once again the continued use of Paternosters was reviewed by HSE with a critical eye. This latest accident occurred in March 2013 when an 81 year old man fell to his death though a fractured floor flap. The author was immediately contacted by Dr Peters and within 24 hours the condition of the flaps, hinges and retaining angles was checked at the Arts Tower. It was concluded that a similar accident would not be possible due to the design of the Schindler equipment which has substantial mild steel supporting frames under the car and landing flaps and the condition of the components which were renewed on refurbishment and found to be good. Once again the Arts Tower Paternoster had survived.

4   CONCLUSIONS

The Paternoster modernisation was a success which delivered a smoother quieter machine with significant improvements to safety driven by analysis of accidents over the previous fifteen years:-

Improved car and landing handle design reduced the risk of trapping and is a method of fall protection whilst in transit.

Improved printed brush mat signage on the car flaps instructs passengers to stand back from the void thus reducing the risk of a fall in transit.

Traffic Light signals on each landing assist inexperienced users to time their entry and exit and reduce the risk of tripping.

The final thought is however for how much longer can the Paternoster survive? We live in an increasingly risk averse society which seeks remedies in the courts in a way which did not exist in the 1960's when this Paternoster was designed. There have recently been a series of very small claims at the Arts Tower for incidents which when seen on cctv appear nothing more than stumbles. ISO TS 14798 correctly identifies the fact that "There can be no absolute safety.., as residual risks can remain… a product or process can therefore only be relatively safe." [3]

Relativity like beauty is a construct of social and cultural influences which change over time and so only time will tell if the author was the last Consultant to modernise a working paternoster.

REFERENCES

[1]   Oriel Chambers in Liverpool in 1868, "In the Footsteps of Peter Ellis." Graham Jones

[2]   Cyclic Elevator, *Wikipedia Paternoster entry*

[3]   ISO TS 14798 2006 (N.B. ISO TS 14798 2013 was not published at the time of the project.)

[4]   Lifting Operations, Lift Equipment Regulations 1998 (LOLER)

[5]   The Provision and Use of Work Equipment Regulations 1998 (PUWER)

[6]   BS2655 part 5 engineering and safety requirements for paternosters.

[7]   BS5655 part 11 Recommendations for the installation of new and the modernization of electric lifts in existing buildings.

[8]   BS EN81 Safety Rules for electric and hydraulic lifts.- Part 80 - Rules for improvement of safety of existing passenger and goods passenger lifts

[9]   The Supply of Machinery (Safety) Regulations 2008

ANNEX 1 SCOPE OF REFURBISHMENT OF THE ARTS TOWER PATERNOSTER

Removal of Paternoster Cars

Carefully remove in correct sequence the remaining 37 paternoster cars so as to avoid an excessive out of balance load on the machine. Degrease clean and label all removable parts including guide shoes to ensure they are refitted to the original position. Transport all 38 cars from site and store in a safe and dry internal location. Allow for storage for a period of 26 weeks. Remove the cast iron paternosters and carry out Non Destructive Testing of the castings. Replace worn bushes as required. Report any defects observed during testing. Any replacement castings required will be subject to an agreed variation order.

Refurbishment of Paternoster cars

Transport the paternoster cars individually or in groups to an approved specialist lift car fabricator. Refurbish each lift car to the standard and finishes shown in ANNEX 2.
The works required are as follows:-
Strip out old carcass back to framework. Inspect framework and report any irregularities if necessary use Non Destructive Testing methods.
De-grease completely, sand down to suit, and paint up original framework in black anti rust paint.
Line out three walls and car ceiling in 12mm plywood face off in following finishes:-
  ▪ Walls – Rimex Cambridge or G Tex Stripes 0.8mm fluted stainless steel
  ▪ Ceiling – White laminate
  ▪ Rear of panels to be painted in intumescent paint
Install new flooring to be in 25mm WBP plywood with a hinged front section in following finishes. Repair or replace hinges as necessary.
  ▪ Floor – agreed colour non slip vinyl
  ▪ Front hinged section – non slip red material signage with all wording required by BS2655 part 5.
Install two special handrails per paternoster car made which are tubular with a sheeted centre section, so as the rail cannot present a trapping hazard either individually or with the similar handrails to be installed on each landing.
Install two angled/sloped bottom sections to stop hinged floor sections remaining in an upright position if lifted.
Install new paternoster car signs, to size and wording defined in BS2655 part 5..
Install access panels in three paternoster cars only in full group for access to certain shaft equipment.
To be a small hinged opening/lockable doorway (x3).
Replace any damaged bows and supporting steel work.
Install new hoods and aprons and replace as necessary all associated framing angled/square as per site dimensions, replace any missing screws.
  ▪ Faces in Cambridge stainless steel
  ▪ Associated framing black.
Load chains

The load chains have been inspected independently by Reynold Chains and Allianz Engineering and have been declared suitable for continued use. Works under this specification are therefore limited to providing a new suitable automatic lubrication system for the chains.

Top Gearing

Provide suitable scaffold platform at the top of the paternoster shaft. Suspend & secure lifting chains. Dismantle & strip out all transmission related equipment. (Guarding and associated fasteners left on site for storage). Remove Transfer and transport all necessary components to approved specialist gear manufacturers works. Fully dismantle, clean and inspect worm gear unit. Re-cut existing worm wheel & manufacture oversize mating worm shaft. Replace all bearings & oil seals; Rebuild, test (standard no load) & paint. Supply first fill of oil. Manufacture & fit new oversize spur gear drive pinion. Dismantle, clean & crack test chain wheel/driven spur wheel assemblies. Verify, by dimensional comparison, suitability of gears for transposition to provide "new" driven tooth flanks. Lightly re-cut worn flanks. Re-assemble with new main spherical roller bearings & pack with initial charge of grease. Dismantle, clean & crack test idler spur gear. Investigate & effect, if appropriate, conversion from plain to rolling element bearings. Re-cut gear teeth to eliminate wear. Re-assemble unit. Dismantle, clean & inspect transfer shaft. Check for straightness. Manufacture & fit new oversize spur gear drive pinions. Supply new plummer block bearings as original. Return to site all transmission system components. Assemble & install and align transmission system. Record all relevant data. Connect electrics. Apply marking blue to gears. Carry out short low speed test run. Record contact patterns obtained (sellotape transfers & photographs). Attach existing chains and run the machine.

Non Destructive Test paternoster chain pins and report any defects.

Bottom gearing and guards and cross beam

Remove bottom sprocket guards. Check the condition of the sprocket and report any defects. Replace the sprocket bearings. Install new bottom sprocket guards. Check condition of cross beam and replace if necessary.

Paternoster Car Guides, Spear points and Chain Guides

Install suitable scaffolding in the Paternoster shaft Replace the damaged sections of Car Guide and Spear points as required. Replace the damaged sections of Chain Guide as required. Remove scaffolding on completion of works.

Reinstallation of refurbished Paternoster Cars

Transport the refurbished lift cars back to site either individually or in groups subject to available storage. Allow for witness inspection of each batch on site by The Vertical Transportation Consultant prior to reinstallation. Check overall cab dimensions, alignment and square. Reinstall 37 Paternoster Cars in correct sequence to avoid excessive out of balance loads. Reinstall the last car at the end of the project prior to final testing.

Electrical Refurbishment

Remove the existing electrical installation retaining only the Landing indicator mechanical components.
Install the following equipment on each landing level:-
- New chord switch across the underside of each landing flap
- 3 off Emergency stop buttons with legend in 10mm high letters
- Two colour (red and green) led illumination in the existing landing floor indicators. Install magnet switches at each landing (and magnets on each car) so that the indicators are illuminated green when a car is within +/- 200mm of floor level and red at all other times.
- Intercom speaker
- Between each landing install recessed LED lighting to give >50 lux illumination in the cars at all points of travel.

Install at the Ground floor a key switch to operate in accordance with BS2655 part 5 clause 2.11.2

Install new shaft lighting to give >50 lux at all areas.

Install interlocked lighting in the top and bottom transfer area so as to interrupt the paternoster control safety circuit in the case of light failure in those areas.

Install photocells to detect car misalignment in the transfer areas.

Install slack chain switches

Install pit stop switch

Install interlocks to pit area access doors

Install additional infrared switch to top landing header flap.

Install 2 off emergency stop switches, one in either side of the machine room

Rewire the electrical installation of the paternoster in accordance with the traditional electrical wiring requirements of this specification.

Install a new VVVF control panel manufactured by approved supplier with remote monitoring system.

Install a remote monitoring station in the porters lodge. NB. IP connections in Machine room and Porters lodge by the University.

Improve machine room lighting to>200lux all areas plus emergency light.

Install an intercom system a to allow 2 way private communication between the Machine room, pit and ground floor as well as public announcements to the intercom speakers on the other levels.

Install voice annunciators to announce standard phrases on restarting the machine which connect to the intercom system.

Landing Equipment Refurbishment

Modify the lower ground floor central architrave so that it can be easily removed with the use of hand tools.

On each landing entrance carry out the following works:-

- Rub down fill and repaint the landing architraves.
- Install new signage in accordance with BS2655 part 5 clause 2.9.2
- Check the landing flaps, hinges and retaining devices, repair or replace as necessary.
- Recover the landing flaps
- Repair or replace landing infill panels.
- Install new handrails to same design as car handrails.

BIOGRAPHICAL DETAILS

Michael Bottomley joined Lerch Bates in 2002 after working for Gregson & Bell Lifts for 21 years. He holds a degree, with honours, in Engineering and Marketing from the University of Huddersfield, and has over 33 years' experience in lift engineering and lift design. In 1999 he was the second lift designer in the UK to achieve Notified Body approval under the Lifts Regulations. He is a member of the International Association of Elevator Engineers and a Past Chairman of the CIBSE lifts group.

The Four Remaining Water Balance Lifts in the UK

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Abstract. In the Victorian and Edwardian eras a number of inclined water balance lifts were installed in the UK. Some of the heritage installations still survive in their water balance format and some have seen conversion to electric motors. As recent as 1991 a new one was installed in Wales and sees regular passenger service. This paper looks at the four water balance units remaining in the UK and compares the clever technologies that were used in their designs. The paper also looks at some of the converted installations which still remain including some which are important means of transport from one part of a town to another. All of the installations are different in their designs and the one thing that they have in common is that they are highly efficient when it comes to the energy they use.

1   INTRODUCTION

Two men were instrumental in the installation of inclined lifts around the UK's coastline. George Croydon Marks (Later Baron Marks of Woolwich) was the engineer and George Newnes was the financier having made his money setting up the "Country Life" series of magazines. The first installation of an inclined lift was at Scarborough in 1875 and they became synonymous with seaside towns such as Folkestone, Hastings, Torquay, Aberystwyth, Bournemouth, and Southend and so on. A few were installed inland but still in popular tourist towns such as Bridgnorth. In the early days some of the lifts were driven by water balance using the volume of water to create a weight differential between two carriages which were linked together. There are two words that have crept into use with these installations namely "lift" and "funicular" both of which are incorrectly used in this concept. They actually fall under the Cableway Installations Regulations 2004 and are "cableways" rather than lifts and the term "funicular" has become the standard way of describing an inclined system where two cabins are linked and one acts as a counterbalance to the other. In fact the term "funicular" technically means "of rope" and could apply to many things. Four water balance lifts remain in service in the UK at Lynton & Lynmouth, Folkestone Leas, Saltburn and Machynlleth. They operate in different ways and demonstrate a wealth of engineering ingenuity which is, of course, where the title engineer was derived from.

2   SALTBURN (1884)

Scarborough's popularity as a resort developed in the 1870's. At the time annual seaside holidays became a national custom. In 1875 the first inclined lift was installed and was a water balance type. It has since been modernised and is now a variable frequency type.

The success of these lifts in aiding tourists to get from the beach to their hotels above on the cliffs caused other seaside towns to consider installing one. Saltburn on Sea was one of those resorts and they ordered a gas engine, water pump and other items of engineering miscellanea from Tangye Engineering Company in Birmingham.

At the time George Croydon Marks was employed by the Tangye company which gained its status as one of leading engineering companies of the time when it assisted Brunel to launch his ship that was firmly stuck on its supports at Millwall – their marketing motto became "Brunel launched us and we launched Brunel!"

Originally Saltburn had a traditional vertical lift of timber construction. The cage could carry 20 passengers and was a traditional counterbalance type and entered service in July 1870.

The original vertical lift

The inclined lift replaced the vertical lift when it opened in June 1884. The track is 207 ft long and the rise is 120 ft. The original gauge was 3 ft 9 in but was relaid to 4 ft ¼ in in 1921. Each cabin has a rated load of 12 passengers and the triangular underframe under each cabin provides the housing for water tanks. In the 1950's the carriages were rebuilt to drawings reflecting the original design.

The original inclined lift

Upon arrival at the bottom station the lower car discharges its water which is pumped back up to the tank of the upper car. There are two water holding tanks the one at the bottom capable of holding 30,000 gallons and the one at the top 18,500 gallons.

The original pump was driven by a gas engine which was changed to a DC generator and motor in 1913 and changed again in the 1930's when it was connected to the mains electrical supply.

The lift as it looks today (2014)

The water cycle for the Saltburn Lift is as follows:

- Cycle starts with water in the top tank (18,500 gallon capacity)
- Water is transferred from the top tank to the tank under the upper carriage
- The system then overhauls with the heavier top carriage with its water lowering whilst the other car ascends
- When the water laden carriage reaches the bottom the tank under it is emptied into a holding tank (30,000 gallon capacity)
- Pumps are used to transfer the water from the lower tank to the upper tank

3   FOLKESTONE LEAS (1885)

Folkestone were not to be outdone! With little room left around the harbour area the building of houses and hotels continued to the west of the town on top of the cliffs but getting down to the harbour and seafront area was a problem for residents and holidaymakers alike. Similarly, getting back up the hill was not for the old, ill or faint hearted so when the idea of a pier was mooted in the early 1880's the time was right to search for a less arduous way of navigating the cliffs. Water balance lifts had already been built in Scarborough (1875) and Saltburn (1884) and appeared to be the solution. The Scarborough Lift still survives but has been converted to electric drive and the Saltburn Lift features elsewhere in this paper. The Folkestone Lift Company was formed and a lease was agreed with the land owner, Lord Radnor.

Reginald Pope, Architect, designed the installation and local builder John Newman constructed the stations. The stations were the first in the town to be constructed using cavity walls which are now employed in the construction of most modern buildings. The lift equipment was provided by Waygood & Company and it opened for service on 21st September 1885.

The weight of water added to the top carriage was used to overcome the weight of the lower carriage and allowed the system to run. The two carriages were rated at 15 persons each and had the familiar triangular shaped water tanks mounted in the chassis.

The lift was an immediate success offering holidaymakers a comfortable ride from the new hotels on The Leas to the bathing facilities on the beach, the "switchback" and the new pier. It was, in fact, so successful that an additional lift, completed in 1890, was added. The second lift was steeper at 42° and as a result toast rack style cars were provided.

The original lift dumped its water onto the beach and proved very expensive for the owners because of the amount used. The addition of the second lift would have made matters worse and it was decided to use the water time and time again by installing a storage and pumping system. This required storage tanks at the bottom and top stations.
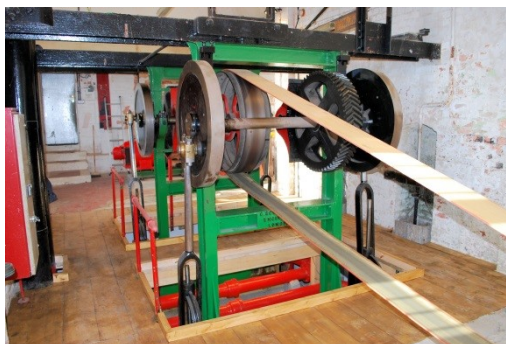
The pump room

In 1899 a second set of storage tanks were added to increase the amount of water that could be stored.

In about 1921 the Crossley gas engines that had driven the pumps for more than 30 years were replaced by electric motors and a band drive facility.
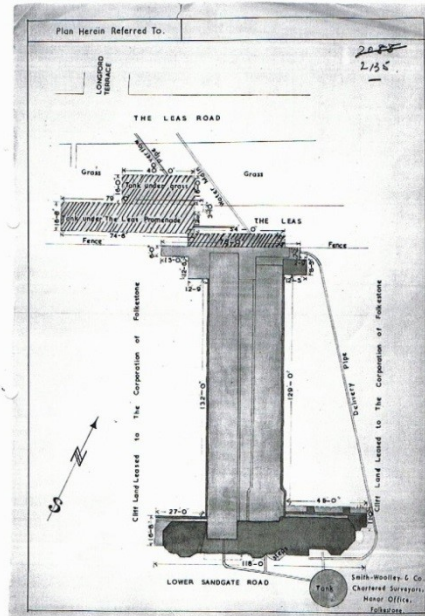
The lift closed during the 2nd World War and became a home guard post. A section of the pier opposite was also removed to prevent invading armies using it. The carriages were lowered to the bottom station thus rendering them useless as well. At the end of the war years of neglect and abuse by the occupying military personnel had left the lifts in a poor state of repair and unusable. It was only a concerted effort by locals that saw the lift reopen in 1947 after a protracted wait for replacement motors which were in short supply at the end of the war.

The heydays of Folkestone had passed with the introduction of overseas package holidays and the 1890 lift carried its last passengers in October 1966. The real reason for the lift being withdrawn was because it had suffered damage following a hard landing and the 1885 lift could cope with the falling numbers of passengers. The lifts insurers though had different ideas and demanded expensive, major improvements that the lift company could not afford and Folkestone Borough Council offered to put up the money in return for taking over the business. As a result the Folkestone Lift Company was forced into liquidation and the lift was absorbed into the local council. In 1974 Shepway District Council took over Folkestone Borough Council and they continued to manage the lift until 2009 when they closed it for economic reasons.

The ownership of the lease reverted to the Folkestone Estate when the lease was surrendered and they carried out a major refurbishment of the lift before looking for a new team to operate it. A group of townspeople got together to form a community interest company and they still run the lift today.

The water cycle for the Folkestone lift is similar to the Saltburn cycle as follows:

- Cycle starts with water in the top tank under the Leas
- Water is transferred from the top tank to the tank under the upper carriage
- The system then overhauls with the heavier top carriage with its water lowering whilst the other car ascends
- When the water laden carriage reaches the bottom the tank under it is emptied into a holding tank
- A couple of times a day the pumps are used to transfer the water from the lower tank to the upper tank

4 LYNTON & LYNMOUTH (1890)

The Lift at Lynton and Lynmouth is a very different design but still uses water ballast as its motive power.

The cliff railway was the second part of a scheme which involved Lynmouth Promenade, Pier and the lift itself.

The cliffs between Lynton at the top and Lynmouth at the bottom posed problems for the growing tourist industry. From the mid 1820's holiday makers began arriving at Lynmouth on paddle steamers from Bristol, Swansea and other Bristol Channel ports but a daunting hill faced those who wanted to walk up to Lynton.

Bob Jones, a local man and partner in the firm that built the esplanade recommended his sisters' son, George Marks, to be the engineering advisor on the project to build the lift.

Marks realised that due to the length of the rails (some 900 ft) rising over 500 ft vertically at an incline of 1:1.75 that he would need to consider safety carefully and particularly the braking system which would need to be far more advanced that those used on its predecessors.

He decided on four separate systems. Two friction brakes which were steel blocks which push down on the crown of the rails by hydraulic pistons and hydraulic callipers which clamp across the crown of the rails.. The system was patented by Marks and the hydraulic system used was filled with water and not oil which became unique to this lift.

The river Lyn, notable for the 1952 floods, would provide the motive power. The Lynmouth & Lynton Lift Company was formed by an Act of Parliament in 1888 which gave the company the perpetual right to extract up to 60,000 gallons of water a day from the River Lyn at the top of the hill. The water passes through a pipe under the road through the town and is held in tanks at the top of the hill adjacent to the top station

The Lynton & Lynmouth Lift in the 1950's

This lift is also different to the other water operated lifts in that space is limited and therefore the two carriages pass in a wide section in the middle of the traverse but spend the rest of their time above and below the passing point in narrower sections.

The water cycle for the Lynton & Lynmouth lift very different to Saltburn & Folkestone and operates as follows:

- Cycle starts with the bottom carriage full of water and held static by the second brake and the diamond lock at the bottom station.

The Diamond Lock

- The top carriage tank is loaded with water (700 gallon capacity)
- When the carriages are ready to move the drivers communicate with each other by bell signals
- The driver of the lower carriage releases the diamond lock and the calliper brake thus leaving the system hanging in suspense.

- The lower driver then releases some of the water from their carriage until the system overhauls
- The overspeed governor automatically applies the brake if the carriages go too fast and it is up to the drive of the lower carriage to keep the speed of the system under the governor speed by using their foot brake to control the speed.

With the water being supplied by the River Lyn and merely being made useful on its way to its discharging into the sea via the lift rather than via the valley it can be seen that the system draws no power and can therefore be deemed as extremely environmentally friendly.

5   MACHYNLLETH (1992)

The Centre for Alternative Technology was a project before its time. It was the place where the idealism of the 1960's met the real world and fought the hard won battle to convince the latter of the virtues of concepts such as sustainable energy sources, energy conservation, organic farming and materials recycling which we readily accept today.

The inclined cliff railway here opened on Saturday 6th June 1992 having been built by the enthusiasts for energy conservation.

The water cycle for this lift is, yet again, different to the other three covered in this paper and operates as follows:

- Cycle starts when the operator at the top station is commanded to fill the top carriage tank as demonstrated below with the carriage away from the station for the benefit of the photo. The water is sourced from a lake at the upper level.

Water Chute

- As the water fills the top carriage tank the drum at the top wants to overhaul which is detected by a tilt switch.
- The top car starts to roll away with the bottom car naturally ascending as their ropes, albeit separate, are wrapped around the same drum
- As the drum rotates it charges an accumulator via a hydraulic pump which is also used to maintain control of the speed
- As the upper car arrives at the bottom the accumulator is used to power the extension of the hydraulic piston which released the water from the carriage that has just arrived at the bottom station.

The water for the operation of the lift comes from a natural lake supplied by rainwater and the system only draws minimal power using a car battery to maintain lighting and switches at the operators console. The movement of the carriages is all down to gravity and costs nothing to operate.

Water being released at the bottom station

6   GEORGE CROYDON MARKS

George Croydon Marks was born on 6th June 1858, the eldest of eight children of which only four survived infancy and followed his father into the Arsenal at Woolwich where he undertook an apprenticeship. At school he had impressed his teachers with his academic ability and it was suggested that he attempt the Whitworth scholarship which he passed and attended Kings College in London achieving a Degree.

At a reasonably young age he became the manager of the hydraulic and lift department of the Birmingham based Tangye Brothers, a company associated with funicular lifts, and was placed in charge of the installation of the funicular at Saltburn. It was here that he met Dugald Clerk, inventor of the two stroke combustion engine, who was to become his business partner.
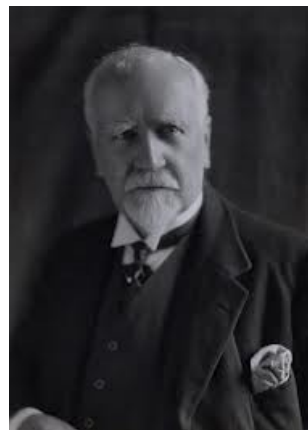
George Croydon Marks

In 1880 he set up in private practice in Birmingham and married Margaret Maynard a year later.

In 1882 (but some reports say 1887) at the age of 29, he set up in private practice as a consulting engineer and was soon joined by Dugald Clerk in the London based patent agency Marks Clerk which still trades today and has offices all round the world

George's mother was originally from Lynton and had maintained contact with her relatives there so once the idea of the Lynton railway became a reality George was brought in to carry out its design. In Lynton he met with George Newnes and each had a profound impact in each other's lives.

Following the opening of the Lynton and Lynmouth funicular Newnes and Marks worked together on a number of funicular installations; Saltburn, in 1892 Bridgnorth, 1893 Bristol Clifton and in 1895 Aberystwyth.

In 1906 he was elected Liberal MP for Launceston & North Cornwall

In 1910 he opened a New York office with Thomas Edison.

In 1911 he was knighted followed by a CBE in 1918. After being elected into the Houses of Parliament he crossed the floor of the house to join the labour party under the leadership of Ramsay McDonald.

In 1929 he was elevated to the peerage and became Baron Marks of Woolwich which was one of the first two Labour peerages

During his life he was a Director of two record companies, Columbia and EMI, and could be described as the Richard Branson of his time. He passed way in Bournemouth on 24th September 1938 whereupon the peerage became extinct.

7   GEORGE NEWNES

Newnes was a man of distinction; born on 13th March 1851, in Bakewell, Derbyshire he was the youngest of 6 children. The son of a congregational minister he was expected to follow his father into the ministry and he was educated in a boarding school where he received preparation for this. He had his own ideas and on leaving school he joined a London firm of accountants as a trainee and later took over their Manchester office. In 1881 he launched the journal "Tit Bits" which was to supply his future funding for some of his projects. It was the success of this magazine that brought him back to London.

In 1885 he was elected as Liberal MP for Newmarket.

The popularity of his publications enabled him to spend the winter in places such as Torquay. In 1887 he was persuaded by Thomas Hewitt, a business man from Lynton to change his plans and he wintered in Lynton and fell in love with this north Devon town. Here he funded the installation of the water balance funicular lift which still exists today.

In 1890, the same year as proposing a cliff lift at Babbacombe, he teamed up with George Croydon Marks, later Baron Marks of Woolwich, who was to be the consultant on the eventual installation at Babbacombe.

In 1895 he lost his Newmarket seat and was given a Baronetcy. In 1897 he started the now renowned journal "Country Life".

In 1900 he was elected MP for the Swansea Town seat although some reports say this was 1906.

George Newnes

He died in 1910 and was buried in Lynton. He never got to see the realisation of his proposal of a cliff lift at Babbacombe although he had his hand in on many cliff railways around the UK including Bridgnorth and Lynton & Lynmouth

8   THE HISTORY OF WATER BALANCE INCLINED LIFTS IN THE UK

The following water balanced inclined lifts were installed in the UK

Date	Location	Gauge	Length	Angle	Notes
1875	Scarborough (Spa)	4 ft 8 ½ in	284 ft	30°	Converted to electric
1878	Scarborough (Queens)	4 ft	218 ft	27°	Withdrawn 1887
1884	Saltburn	3 ft 9 in	207 ft	30°	Still in service
1885	Folkestone Leas	5 ft 10 in	164 ft	32°	Still in service
1890	Folkestone Leas (2)	5 ft	155 ft	34°	Withdrawn 1966
1890	Lynton & Lynmouth	3 ft 8 in	862 ft	30°	Still in service
1890	Laxey	5 ft	300 ft	14°	Withdrawn 1914
1892	Bridgnorth	3 ft 8 ½ in	201 ft	29°	Converted to electric
1893	Bristol	3 ft 8 in	450 ft	22°	Withdrawn 1934
1893	Folkestone (Sandgate)	5 ft 6 in	670 ft	12°	Withdrawn 1918
1896	Aberystwyth	4 ft 10 in	798 ft	27°	Converted to electric
1903	Hastings (East Hill)	5 ft	267 ft	38°	Converted to electric
1904	Folkestone (Metropole)	5 ft 6 in	96 ft	36°	Withdrawn 1940
1992	Machynlleth	5 ft 3 in	197 ft	29°	Still in service

9   CONCLUSION

14 water balance inclined lifts were installed in the UK of which only 4 remain at Saltburn, Folkestone, Lynton & Lynmouth and Machynlleth.

Whilst the 4 remaining inclined lifts have different modus operandi they all have two things in common – they use water as the prime mover and they are incredibly efficient when it comes to energy consumption.

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BIOGRAPHY

David Cooper has been in the lift industry since 1980 when he started an apprenticeship with British Railways. He has been involved with many of the rail mounted inclined lifts around the UK including Hastings East, Hastings West, Babbacombe, Scarborough Central, Scarborough South Cliff, Scarborough St Nicholas, Padstow, Lizard, Southend, Urbis Centre, Machynlleth, Bridgnorth. Internationally he has also been involved with the Angels Flight inclined lift in Los Angeles. In 2008 he appeared in the BBC programme "Flog It" as the expert showing Paul Martin over the Inclined Lift at Babbacombe in Devon. He has won awards for his involvement with inclined lifts including the Association for Consulting and Engineering Awards for the projects at Babbacombe and Hastings. He has also been involved with aerial suspended cableways and was the winning project in the Elevator World Project of the Year in 2013 for the London Emirates Airline Cable Car on which he presented a paper at the 2013 Symposium.

The Importance of Choosing the Correct Door for Different Applications

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Abstract. Each specific installation requires lift doors with distinctive, well defined features and technical characteristics, which allow to satisfy the expectations and needs, not only of those who designed the lift system, but also of those who designed the whole building and, above all, of those who will use it. The functional and aesthetic characteristics of automatic lift doors are always combined with the essential requirements of product described by the European and International standard for the lift sector which, in many cases, significantly contribute to the definition of the distinctive characteristics of the component "door" for each application context.

In the paper we will present some of the solutions that lift door manufacturers can offer to customers, architects, designers and installers even for the most complex and technically demanding projects: from standard to tailor-made automatic doors for any type of elevator, both for people and goods transportation, in skyscrapers, residential, civil, commercial and industrial buildings, as well as in hotels, hospitals and cruise ships. In order to improve the efficiency of any complete lift system, each lift door (and its components) should be specially designed and manufactured in order to offer customers the best possible solution for each specific application and requirement through the perfect combination of technology, functionality, security, comfort and innovative aesthetic solutions.

1   INTRODUCTION

Each specific installation requires lift doors with distinctive, well defined features and technical characteristics, which allow to satisfy the expectations and needs, not only of those who designed the lift system, but also of those who designed the whole building and, above all, of those who will use it.

The characteristics and intended uses of each building influence and affect the design of lift systems and their components, including doors. For example, due to the heavier use and higher traffic conditions, a public building or station will require lifts with higher resistance to vandalism than the ones of a private apartment block, which is inhabited and used only by a few families; an high-rise office building or a luxury 30-floor hotel should integrate more performing vertical transportation solutions and more prestigious finishes than industrial lifts used to transport goods and materials.

But building type is not the only criteria that has to be considered in the selection of elevator equipment; cabin capacity, speed, rise and, above all, standards are essential variables too. Focusing on lift doors, this means that during the design phase the functional and aesthetic characteristics of the doors have to be always combined with the essential requirements of the product described by the European and International Standard for the lift sector which, in many cases, significantly contribute to the definition of the essential characteristics of the component "door" for each application context.

For instance the new EN 81-20 will introduce some relevant changes, related to the safety of the passengers and the safety of the workers during installation and maintenance, that all the door manufacturers have to take into consideration in the development of their new products as well as in the improvement of their existing products, which are not compliant to the new European requirements.

2   MAIN APPLICATION CONTEXTS

Any lift type suitable for a specific application context presents well-defined, general characteristics that are strictly linked to its intended final use (see Table 1). A freight lift should be designed to maximize its resistance against potential hits and withstand heavy loads (forklifts etc.); an high speed lift should include specific devices in order to minimize noise and vibrations; a panoramic lift should feature aesthetics solutions, such as glass walls, and comfort devices that will enhance passengers' travel experience.

Table 1 Lift characteristics per application context

Lift type / Characteristics	High speed	Freight	Inclined	Vandal resistant	Modernization	Panoramic
Performance	••••• traffic management	••	•••	•••	•••	•••
Reliability	••••• high traffic application	•••	•••• optical coupling	•••• Installation in public places	•••	•••• high traffic application
Adaptability	•••	•••	••••• To different job site conditions	•••	•••	•••
Resistance	•••	••••• against potential hits	•••	••••• against vandalism	•••	•••
Accessibility	•••	•••	•••	•••	••••• small shaft dimensions	•••
Aesthetics	•••• top architectural projects	••	•••	••	•••	••••• iconic element of the building
Comfort	••••• noise, vibrations	•••	•••	•••	•••	•••• passengers' travel experience
Robustness	•••	••••• withstand heavy loads	•••	•••• withstand adverse conditions	••	••

Table 1: Correlation between lift type and general lift characteristics – source Sematic

Also all of the components of any type of lift should be designed, manufactured and fine-tuned according to building type and application context. For lift doors this means acting on a series of variables such as dimensions (width and height), type of openings, resistance to wearing of the door parts, opening and closing times, weight of the panels (see table 2), which all contributes to the overall performances of the lift in a specific context of use.

Table 2 Lift doors characteristics per application context

Typical application	Residential - offices	Modernizations	Goods transport	Heavy duty industrial	High traffic-flow high rise
Useful life (cycles)	7,8 mln	7,8 mln	7,8 mln	9 mln	11 mln
Door Panels mass	4x23 kg	8x12 kg	8x22 kg	12x50 kg	4x25 kg
Type of door	2 panels center opening	4 panels center opening	4 panels center opening	6 panels center opening	2 panels center opening
Avg. Width	1.100	800	1.400	2.400	1.100
Avg. Height	2.000	2.000	2.400	3.500	2.200
Average car door cycles per year	500.000	500.000	650.000	650.000	900.000
Opening time (default profile)	1.9 s	1.6 s	2.2 s	2.4 s	1.4 s
Closing time (default profile)	2.6 s	2.0 s	3.2 s	6.5 s	1.9 s

Table 2. Lift door typical characteristics per application context – source Sematic

2.1   High speed lifts

High speed is the most advanced application in the lift industry. Typically installed in residential and commercial high rise buildings with high traffic flows, super-fast complete lift systems, as well as all of their components, must guarantee top performances together with maximum safety and comfort.

High rise buildings have distinctive external, internal and regulatory characteristics that require special skills for the design and construction of their vertical transportation systems as well as of all of their components. Together with the need for longer shafts and higher transport speed, a number of specific factors, which are normally not significant in ordinary buildings due to low speed and air flows, must be kept under control during the design of high rise elevators, considering that high performances have to couple with strict constraints.

In high rise elevator design, the doors play a key role since they are the most critical device in terms of people safety, and also affect the overall performances of the system; therefore, one of the main concerns is allowing the door systems to work in the best conditions.

The starting point for achieving this goal is clearly defining all the variables that have impact on the doors systems (see table 3).

Table 3 Variables to be considered in the designing of lift doors per high rise buildings

In the building variables	Out of the building variables	Door specific variables
Height of the building	Fire and smoke	Performances required
Flow management	Wind	Quality perceived
Positive and negative pressure in the shaft well	Evacuation situations	Reliability
Tolerances in clearances of mechanical elements	Extreme weather conditions	Aesthetic requirements
Turbulences and vibrations	Regulatory environment	Energy efficiency and safety of the system
Management in case of power loss		Integration with other systems

Table 3: Variables to be considered in high rise buildings – source Sematic

The first group of variables identifies the status of the building in terms of structural configuration, population, flow management, etc. Each of these variables is responsible for specific effects that have to be carefully considered. For example the height of the building (i.e. of the shaft well), determines air pressure, which generate stack and piston effects. In such tall shaft-wells in fact, pressure can be so high that doors may experience difficulties in the very last part of the closing phase, resulting in reliability problems if not properly managed.

The influence of external factors must not be undervalued too, affecting door design and thus construction. These variables are normally codified in standards, norms, recommendations, specifications and strongly affect the doors systems. Fire and smoke regulations are probably one of the most critical topic. In high rise buildings some risks, such as fire and smoke propagation, are amplified by the structure of the building itself (lengths of shafts and consequent stack effect); poor protective systems of any building equipment can lead to disastrous consequences.

So satisfying top safety requirements is a must not only for architects and designers but also for the manufacturers of all the service facilities of the building, including elevator and elevator component manufacturers. A high rise elevator system must be able to safely manage any emergency and must be designed with special components (fire-resistant; vandal-resistant; etc.) and materials (i.e. non-combustible) that, for example, in case of fire do not permit the propagation of flames and smoke.

International, European (EN 81-58) and local standards, norms, recommendations, specifications give some guidelines and hints to design safe components in elevator systems as well as to improve their fire resistance. Firefighters elevators and fire-resistant components are among the solutions that the elevator industry offers to increase the safety in high rise buildings. Furthermore also the

introduction of new standards, such as for example the EN 81-20 and EN 81-50, can considerably impact on elevator door design and manufacturing.

The last group of variables is related to the door systems only, which includes: performances required in terms of opening/closing cycles (which affect significantly travel time), quality perceived (noise, vibrations, smooth profiles), reliability both in terms of call-back rate and preservation of performance and quality over time, energy-saving, safety and aesthetics (design and flexibility to suit different claddings and executions, together with the ability to master glass for example).

Considering all these variables automatic lift doors for high speed lifts must feature high adjustability, reinforced and high performing components, panels and headers, that are designed to move heavy panels in short times and with low noise emissions. Their main characteristics can be defined as the followings:

- Performances (speed in terms of opening and closing time: 1,4 s + 1,9 s for high rise elevator doors vs 1,9 s + 2,6 s for standard elevator doors)
- Reliability (life cycles)
- Robustness (increased panel masses)

To satisfy all these requirements, door manufacturers have developed a complete range of solutions, which includes special features of the door drive controllers (adjustable opening and closing speed profiles; real-time moving mass calculation algorithm; speed profile automatic downgrade; stand-by mode; battery back-up) or specific mechanical devices in order to take care, for example, of sealing the cabin and landing doors during the elevator ride (increasing comfort).

2.2   Freight lifts

Freight lifts are used to transport goods in airports, undergrounds, railway stations, shopping centres, hospitals (e.g. for stretchers), industrial premises and parking lots; contexts where resistance and durability of all the components are crucial. In particular, automatic doors for freight lifts must withstand heavy loads (i.e. forklift) and potential hits, so they need to be not only robust, but they have also to guarantee high level of service and reliability in all operative conditions, even in the extreme ones.

Automatic lift doors, which openings can reach even 6000 x 5000 mm, satisfy these requirements thanks to a set of constructive solutions specially designed for this application such as reinforced clutch, frames, panels, hangers, bigger rollers as well as upper and bottom tracks in high resistance materials (i.e. steel, extra-reinforced steel – see table 4).

This set of constructive solutions enables the doors to withstand the impact of a collision with vehicles (i.e. forklifts, mobility scooter, objects) and guarantees that the door panels stay in their position and don't exit from their bottom track guides in case of accident, preventing people and objects from falling into the shaft. Also installation mode contributes in enhancing the stability of the entire door systems, for example with the partial installation of door posts on the floor.

Table 4 Correlation between sill types and application contexts

Elevator rated load (Kg)[1]					
Private, office, hotels, hospitals	Freights (standard)	Freights (forklift / pallet)	Suitable sill and support types	Sill load (Kg)	Concentrated load (Kg)
4.000	2.600	1.800	Standard aluminium sill with reinforced brackets	1.600	800
---	6.600	4.700	Reinforced aluminium sill with reinforced brackets	4.000	2.000
---	13.300	9.400	Steel / stainless steel sill with full width angular support	8.000	4.000
---	> 13.300		Reinforced steel / stainless steel sill with full width angular support	> 8.000	> 4.000

Table 4: Correlation between sill types and application contexts – Source Sematic

2.3   Inclined lifts

Inclined lifts allow the overcoming of slopes and guarantee transport between different levels on an oblique path. The lifts used for this purpose always include high tech solutions and must guarantee a high degree of adaptability to the different job site conditions, which include also the impossibility of mechanical coupling of car and landing doors, one of the fundamental working aspects of this specific component.

To solve this problem some door manufacturers have developed doors with optical coupling. Here follows an example of its working: car and landing doors are both equipped with linear belt traction operators, each one with its own engine, and couple through an optical device, which should allow only a minimum misalignment between the centres of the emitter and the detector.

As prescribed by the recently released EN 81-22, optical coupled doors for inclined lifts must guarantee the perfect functioning of the systems on levels with inclinations, usually between 15° and 75° are allowed, and, for complex installations, it's even possible to have different inclinations from floor to floor. Since this type of lifts are often installed outdoor also the protection of the components is fundamental, for example a fully covered operator with high IP rating and materials that guarantee satisfactory performances even in extreme weather conditions.

2.4   Vandal resistant lifts

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[1] The relation between the sill load and the elevator rated load is calculated according to EN 81 standard as following:
- Elevators with rated loads less than 2500 kg in private premises, office buildings, hotels: 0,4 x Elevator rated load;
- Elevators with rated loads of 2500 kg or more: 0,6 x Elevator rated load;
- Elevators with rated loads of 2500 kg or more in case of forklift truck loading: 0,85 x Elevator rated load

Unluckily the lifts installed in public places, such as stadiums, airports, underground and train stations, schools, universities and public parking, are often subject to vandalism. Even if it's quite impossible to develop a 100% vandal-proof system, the lift industry's efforts to improve lifts' resistance to vandals' destructive tendencies have already achieved significant results.

Component manufacturers have developed a wide range of solutions that contribute to the improvement of the overall lifts' safety. If we speak about doors these instances are translated into a series of precautions, which make the system more robust and resistant to damage and breaking.

As prescribed by EN 81-71 standard, for the landing doors these precautions includes, for example, mechanism cover plate, protected emergency unlocking device, corrosive fluid resistant bottom track and reinforced panels with adequate thickness and made in anti-scratch materials. In addition to all these safety measures, for the car doors, attention has to be paid to prevent its forced opening, that can cause serious hazard, through special car door locking devices. Furthermore as per EN 81-71 class 2 requirements, door construction should not include the use of rubber profile and detector on the panels beating edge as well as of vision panels (allowed for class 1).

2.5   Lifts to be modernized

Lift modernization projects aim to improve safety, accessibility, reliability, efficiency, performances and comfort in existing systems, whilst simultaneously lowering maintenance activities and energy consumption.

Door manufacturers are able to offer a wide range of solutions for the complete replacement of old lift doors (both manual and automatic), as well as of some of their key components. In this market segment, the product offer is suitable for an extensive range of existing installations and customized according to the different destination markets and their characteristics, such as for example shaft dimensions or local regulations.

Space saving of the components is one of the most important issues in order to maximize cabin capacity and accessibility; to reach these goals, bottom track packages with minimal amount of space (approx. 115 mm), availability of non-conventional opening types (i.e. asymmetric opening), frameless doors and recess installation are just few examples of the solutions that can be adopted.

2.6   Panoramic lifts

Lifts aren't always just about moving people; sometimes they can be a distinctive, iconic feature of the building itself. Aside from their functional ability, panoramic lifts can be a focal point of any building providing a combination of elegant finishes and all-round visibility – ideal for making the most, for example, of an open hotel foyer or a shopping centre atrium.

Each panoramic lift can be tailor-manufactured to suit a particular architectural requirement or design concept and its components must be customized in order to guarantee the best possible aesthetic and functional performances.

For automatic lift doors these requirements are satisfied through material selection (full or framed glass panels), panel shape (round doors) and special executions such as doors with hidden bottom tracks or doors with under-driven operators, which comprise exclusive design advantages such as for example reducing the visible size of the car door operator from the floor hiding the lift door mechanisms under the floor level.

Focusing the attention on glass panels, the new EN 81-20 (see also paragraph 3) introduces a series of means to minimise the risk of dragging of children hands, one of the typical threats for this type of doors. According to the new standards, automatic power operated horizontally sliding doors made of glass shall be provided with means to minimise this risk, for example, by making the glass

opaque on the side exposed to the user by the use of either frosted glass or the application of frosted material to a height of minimum 1,10 m or by sensing the presence of fingers at least up to 1,6 m above sill and stopping the door movement in opening direction, or by limiting the gap between door panels and frame to maximum 4 mm at least up to a minimum of 1,6 m above sill.

THE NEW EUROPEAN STANDARD: EN 81-20

If application context characteristics are relevant to the design and manufacturing of lift doors, standards are even more influencing factors. The new EN 81-20 will have for sure a deep impact on the design and development of lift systems and components for the next decades and one of the largest changes it will introduce is related to car and landing doors, for every type of lift.

The new European standard require, for example, that doors will be increased in strength and their integrity will be improved under impact conditions. All of the landing doors will need to successfully pass a pendulum shock test, and the forces (300 N for concentrated load and 1000N for distributed load) that they have to withstand are well increased compared to EN 81-1/2. After such testing the doors must be within certain defined limits regarding permanent deformation. Some products on the market are already compliant with these new requirements, some others will need a revision of their designs, including for example the addition of reinforcing profiles and stabilizing elements on the panel ends, in order to satisfy the more stringent testing requirements.

These changes are necessary to increase the robustness of the doors and, together with the prescription of using additional retainers, to hold the door panels in position in case of a consistent impact when the main guiding elements of the door fail. These precautions will prevent accidents, even dangerous, which imply the falling in the shaft of people and goods.

From the passenger's safety perspective, another significant change will be related to the protection from being hit by closing doors. Investigations carried out by national and European lift associations show that the collision with the doors during their closing phase is one of the leading causes of injury in lifts, especially for elderly people.

EN 81-20 defines that automatic power operated doors must be fitted with non-contact protection devices that shall automatically initiate the re-opening of the doors or take the lift out of service in the event of a person crossing the entrance during the closing movement. This prescription includes stringent requirements regarding the position and coverage of the device (between 25 and 1600 mm above the car door sill), the minimum dimension of obstacles to be detected (50 mm diameter) as well as the kinetic energy at the average closing speed (limited to 10 J with the protective device perfectly working and to 4 J when deactivated).

For glass doors, protection is even increased (see also paragraph 2.6). They will have to be provided with means to limit the opening force to 150 N and to stop the doors in the event of obstruction as well as with thickness, gaps and sensors that will avoid the dragging of children's hands.

For the safety of the workers during installation and maintenance, new limitations have been placed on the height of the unlocking mechanism to avoid persons falling into the shaft whilst trying to unlock and open doors at the same time. Also, a "bypass operation" for the car and landing door locks has been added. Workers sometimes need to over connect contacts to determine the cause of the failure in a lift, but there is a risk that they may forget to remove those over connections, causing enormous risk when the lift is in normal operation. EN 81-20 describes how to avoid it.

3   CONCLUSIONS

New standards and directives as well as a better understanding of the application contexts and intended uses of lifts give door manufacturers motives to improve and develop their products.

The correct approach for the design and development of lift doors, in order to give lift companies the best possible components for the intended use of their lift systems, is than to combine all the regulatory and technical aspects which are relevant to tackle the application context issues, such as for example, safety, speed, reliability, perceived quality and comfort, together with the non-technical requirements (aesthetics) posed by architects, engineering and construction firms.

Lift doors must be seen not only as a component of the lift but as a perfectly integrated and connected piece of the building/context where they are installed.

BIOGRAPHICAL DETAILS

Born in 1973, Giuseppe De Francesco holds a degree in Electronic Engineering from the Politecnico of Milan. Since 2002 he has been working in the Sematic Group, holding positions of increasing responsibility in the Engineering and R&D areas of the company. Nowadays he is responsible for all the product development activities of Sematic worldwide. Having 12-year experience in the elevator industry, Mr. De Francesco has gained significant know-how and expertise in the development of innovative solutions for the design and manufacturing of automatic elevator doors, including glass and fire-resistant executions, in any application context: from high-rise to modernization.

Reverse Journeys and Destination Control

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Abstract. When a passenger gets into a lift, he or she expects to be taken in the direction of their destination. A reverse journey, where the passenger is initially taken up when the call is in the down direction, or vice versa can be disconcerting. Reverse journeys can be avoided with destination control, but only if the system is allowed to refuse calls. Refusing calls, with a "no lift available, please try again later" message or indication is frustrating for passengers. This paper explores why destination control systems are susceptible to reverse journeys and how lift planning affects this issue. Where accepting a reverse journey is the best compromise, appropriate indication can help to avoid passenger confusion. Allowing reverse journeys has an impact on handling capacity and quality of service. These factors are investigated using simulation.

1 INTRODUCTION

1.1 Background

The control of a group of lifts to serve registered hall calls and car calls can be divided into two levels [1]. The higher level elevator dispatching problem can be considered as an assignment problem. The lower level is self-contained, can be treated as a set of a travelling salesman problem and is traditionally solved with collective control [2]. The lower level describes the control algorithm of a single car to serve its registered calls based on a set of rules and constrains [2, 3, 4]:

- Do not bypass a car call/destination of a passenger
- Do not transport passengers away from their destination
- Only stop at a floor because of a car call or hall call

These rules alleviate the psychological aspects passengers feel by avoiding reverse journeys and unnecessary, blind stops.

1.2 Reversed journey in conventional systems

Reverse journeys are not difficult to avoid with conventional collective control where there are up and down landing call buttons. EN81-70 requires direction indicators for conventional control systems [5]. In most cases, the car allocation is only revealed shortly before a car arrives at the landing: passengers travelling up get into the car when the lift stops on its way up with the up indicator lit; passengers travelling down get into the car when the lift stops on its way down with the down indicator lit. This means that the same car can be allocated both an up and a down call on the same floor without resulting in reverse journeys.

Reverse journeys do occur, but only when passengers do not recognize the announcement, or if they deliberately choose a reverse journey. Sometimes choosing a reverse journey can result in a shorter time to destination and passengers' recognition of this has been observed in heavily loaded systems. Some passengers press both pushbuttons with the hope of a faster car arrival. Sometimes passengers enter a lift although it announces the opposite direction. In these cases passengers get into the lift knowing that they will ultimately get to their destination, or do not see/understand the announcement.

1.3 Reverse journey in destination control systems.

In destination control systems the passenger selects the floor he or she is travelling to, and is told immediately which car to use. Each lift entrance needs to be individually marked and needs to be easily identified [5]. When the car arrives, no direction information is provided. Since the passengers are waiting in front of the allocated lift, hall gongs and lanterns are not needed [6]. Some installations include indicators to reassure passengers that they are waiting in front of the correct car for their destination. When the car arrives, it is normal to have an in-car indication of the planned stops.

Reverse journeys can be avoided with destination control, but only if the system is allowed to refuse calls [7]. Refusing calls, with a "no lift available, please again try later" message or indication is frustrating for passengers. It can also lead to a significant increase in waiting times. For these reasons people designing and configuring destination control dispatchers sometimes allow reverse journeys.

1.4 Reverse journey scenarios

Figure 1 illustrates three separate scenarios where accepting a new allocation will cause a reverse journey. In scenario A and C the new call causes a reverse journey for existing passengers. Scenario B causes a reverse journey for the new call. In scenario C the reverse journey is caused by the combination of three calls.

Some systems may stop twice at the same floor. For example, in scenario A the lift could stop at the ground floor in both in the down, and then up direction. However, as passengers enter the allocated lift when it opens the doors independent from any direction indicators, in practice the second stop is not required and can be avoided. However, space in the car for passengers who start their travel time in the wrong direction should be considered.

In many cases the reverse journey can be avoided simply by choosing another car. However, a combination of the scenarios described happening together results in their being times where the choice is to accept the reverse journey, or to refuse calls with a "no lift available, please again try later" message. This is illustrated for two lifts in Figure 2, but also occurs with larger groups when there are more calls.
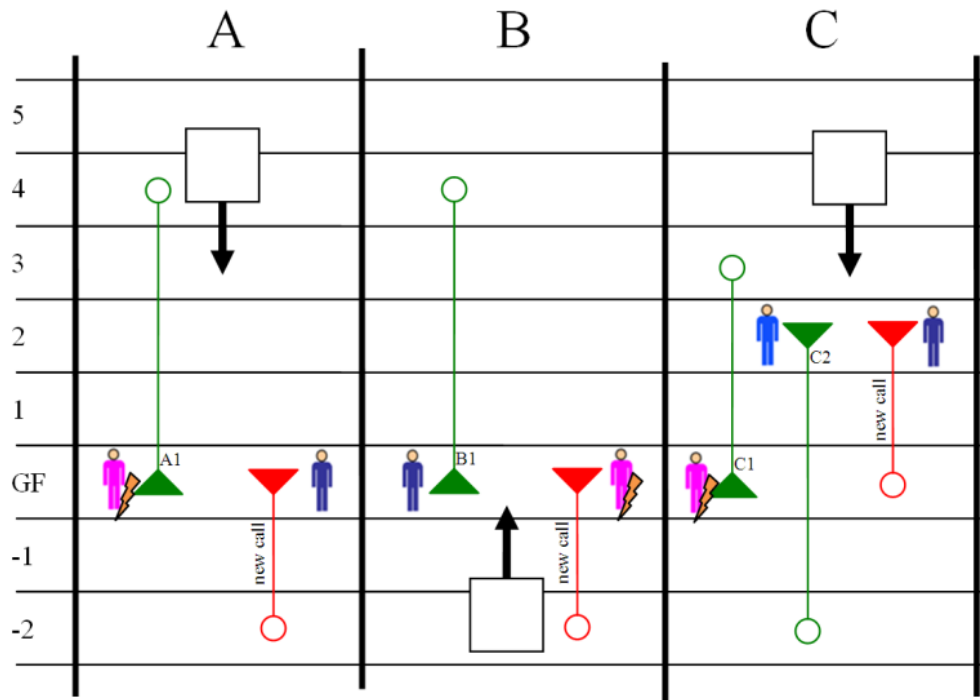
Scenario	Order of stops	
	Without new call	**With new call**
A	GF, 4	GF, -2, 4 (reversal for A1 at GF)
B	GF, 4	GF, 4, -2
C	2, -2, GF, 3	2, GF, -2, 3 (reversal for C1 at GF)

Figure 1 Reverse journey scenarios with single lifts
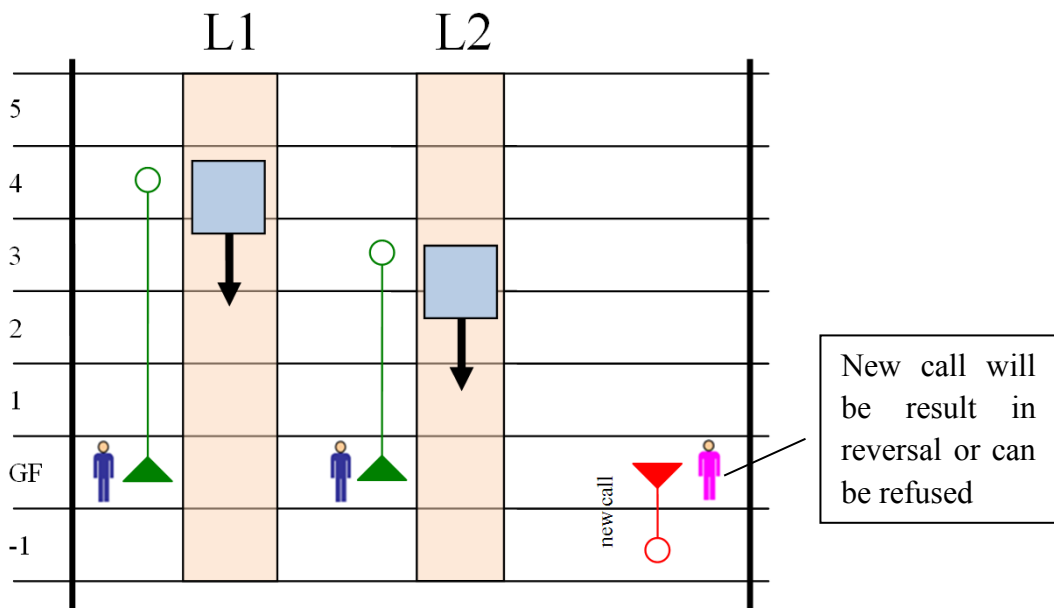
Figure 2 Reverse journey scenario with two lift group

2 REVERSALS AND PERFORMANCE

When destination control systems are saturated not all passengers receive an immediate allocation [8] and the system refuses calls[1]. Excluding allocations that cause reverse journeys limits the dispatcher's options and makes refusals more likely at lower levels of demand, prior to saturation. Refusals are more irritating to passengers than reverse journeys [7]. So, the option to allow reverse journeys should be considered.

Lift performance has been compared in destination control systems where reverse journeys are and are not permitted; it was shown that the results for the average time to destination are better [10] if reverse journeys are allowed. However the work was based on a single car operation and does not discuss the dispatching problem.

In this paper the effect of reverse journeys on a lift group is considered, applying the ETD algorithm [11]. The sample building has 6 1600 kg lifts @ 2.5 m/s serving 14 floors above the entrance level(s), with a population of 60 persons per floor (20 persons on top floor). For simplicity, the initial results are based on a 4 hour simulation with constant traffic demand of 12% of population per five minutes.

3 REVERSE JOURNEYS IN OFFICE BUILDINGS

3.1 Morning up peak

In an office building during the morning up peak, the traffic is typically split 85% incoming, 10% outgoing and 5% interfloor [12]. For the sample office building with a single entrance, Figure 3 compares average waiting time and transit time results with and without reverse journeys allowed. Where reverse journeys are allowed, the number of reverse journeys per five minutes is also plotted.
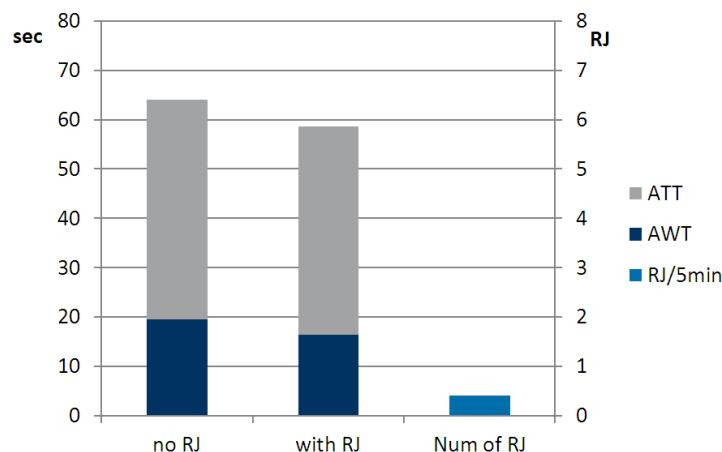
Figure 3 Comparative performance for sample office building during up peak with and without reverse journeys allowed

3.2 Lunch peak

During the lunch period, a typical traffic split is 45% incoming, 45% outgoing and 10% interfloor [12]. Figure 4 shows simulation results for this lunch time split, with and without reverse journeys. As would be expected intuitively, with the traffic more evenly divided in the up and down directions, there are more reverse journeys (if allowed). As the dispatcher optimisation process only

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[1] Saturation control strategy for destination control systems is discussed elsewhere [9].

chooses a reverse journey when it improves the time to destination, the performance improvements are more significant than for up peak traffic.
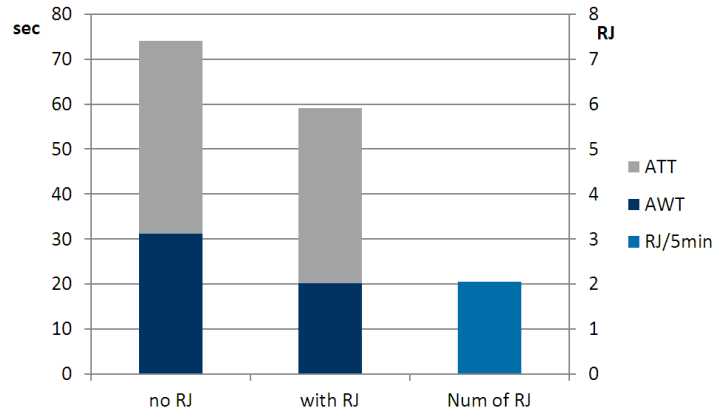
Figure 4 Comparative performance for sample office building during lunch traffic with and without reverse journeys allowed

4   IMPLCATIONS OF DESIGN CHOICES

4.1   Not all lifts serve all floors

A commonsense rule of group lift designs is that all lifts in a group should serve the same floors [6]. Ignoring this rule is generally a false economy. If it is for some reason not possible to let all lifts serve all floors it is a good choice to use a destination control system as the system knows which lift serves a passenger's arrival and destination floor [7]. However reverse journey situations are more likely because less lifts are available for some trips. An example is given in Figure 5. The new call can only be served by L3. An allocation of the new call causes a reverse journey for the passenger waiting on floor 2. If the control system excludes allocations with reverse journeys, the call must be refused.
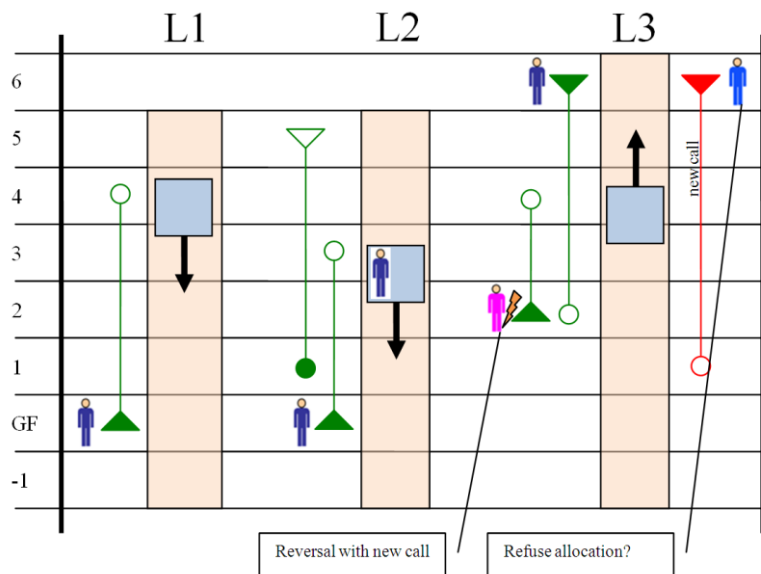
Figure 5 Reverse journeys become more likely when not all lifts serve all floors

To demonstrate the effect of one lift not serving the top floor, the simulation yielding results in Figure 4 was repeated with only one lift serving the top floor. The results in Figure 6 demonstrate the impact on performance by not having all lifts serve all floors. However, by allowing reverse journeys the degradation of performance is reduced.
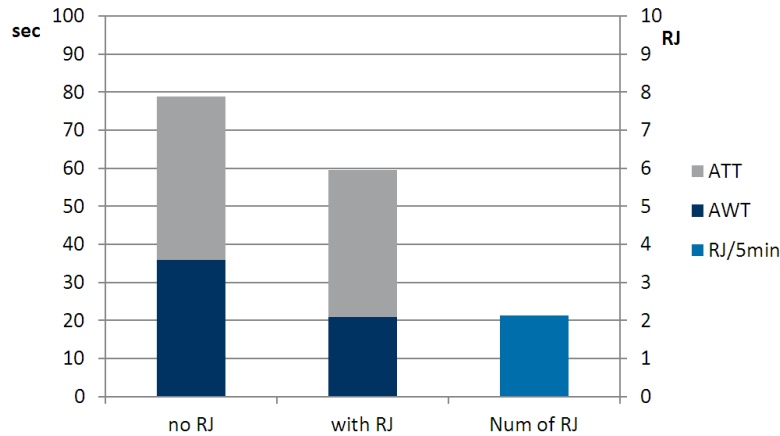
Figure 6 Results showing allowing reverse journeys reduces the degradation in performance caused by not all lifts serving all floors

4.2   Multiple entrance floors

Some buildings have multiple entrance floors. These multiple entrance floors can be at different street levels or serve car parks in basement floors below the main entrance lobby. An entrance floor becomes relevant if there is a significant number of passengers boarding and alighting the lifts. Multiple entrance floors result in additional stops which have an effect on the round trip time, impacting both quality of service and handling capacity. Shuttle lifts or escalators carrying people from the basement floors to main entrance help to eliminate these additional stops [6].
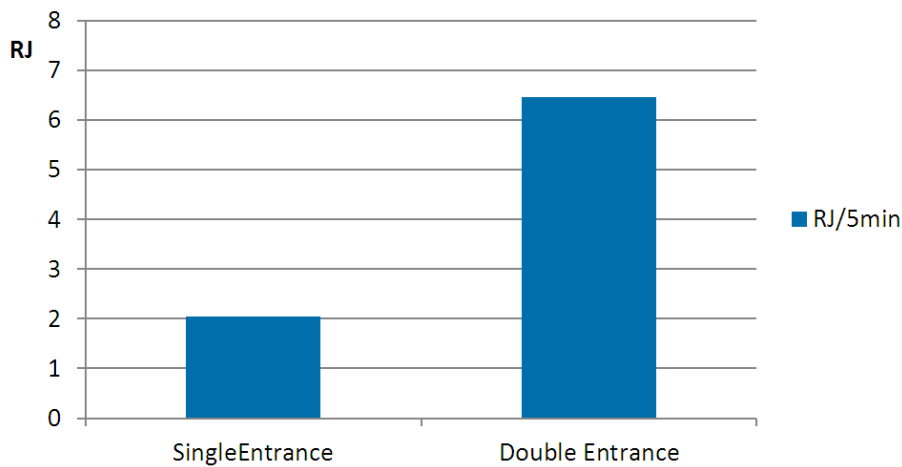
Figure 7 Results showing the multiple entrance floors are more susceptible to reverse journeys

Buildings with multiple entrance floors with mixed traffic are particularly susceptible to reverse journeys at peak times. This is because any lift stopping at an upper entrance for a passenger to alight is also likely to have been allocated an up call from this entrance. Figure 7 shows the number of reverse journeys for the sample building with a single and double entrance. For the double entrance simulation, the entrance bias was 50% to each floor. The traffic was split is 45% incoming, 45% outgoing and 10% interfloor. If reverse journeys are not allowed, there is a corresponding increase in waiting time.

4.3   Restaurant, meeting and other busy floors

Many office buildings have dedicated staff restaurants [13] that affect the morning and the lunch traffic. Restaurants, meeting rooms, and other busy floors should preferably be located in the

basement or on the second floor and should be served separately by escalators or shuttle lifts. The traffic of restaurants floors can be treated as additional entrance floors [6]. Strakosch recommends never locating a restaurant/cafeteria at an intermediate floor of a lift group [6]. As with multiple entrance floors, these busy floors are particularly susceptible to reverse journeys at peak times.

5   DESIGN APPLICATION

The simulation in earlier sections are indicative of what factors affect the number of reverse journeys that occur if allowed, or the impact on waiting and transit time if they are not. However, it is difficult to generalise these results as there are many parameters, and the performance of lift systems is not linear. For building specific advice, demand templates based on actual traffic demand are more useful. Figure 8 provides a sample office building demand template [14]. This has been applied to a 6 car lift group serving 14 floors above two entrance levels (average of 4 runs).
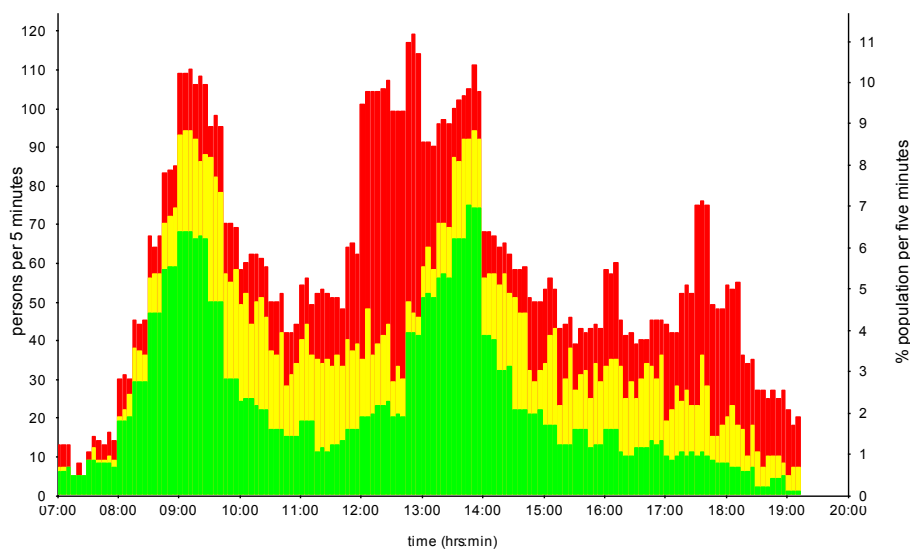
Figure 8 Siikonen full day office template

Without reverse journeys, the waiting and time to destination plotted throughout the working day are as indicated in Figure 9.
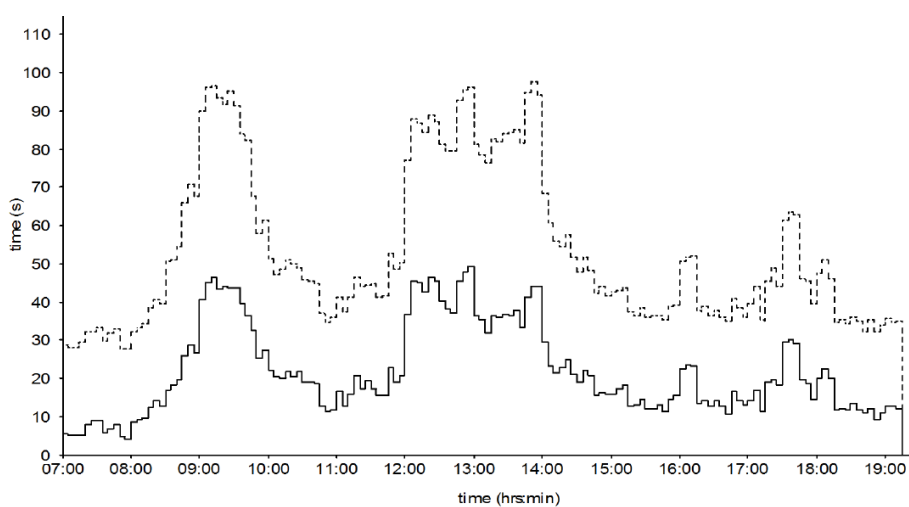
Figure 9 Waiting time (solid line) and time to destination (dotted line) without reverse journeys

Allowing reverse journeys, the waiting and time to destination plotted throughout the working day are as indicated in Figure 10. The number of reverse journeys plotted by time of day is given in Figure 11.
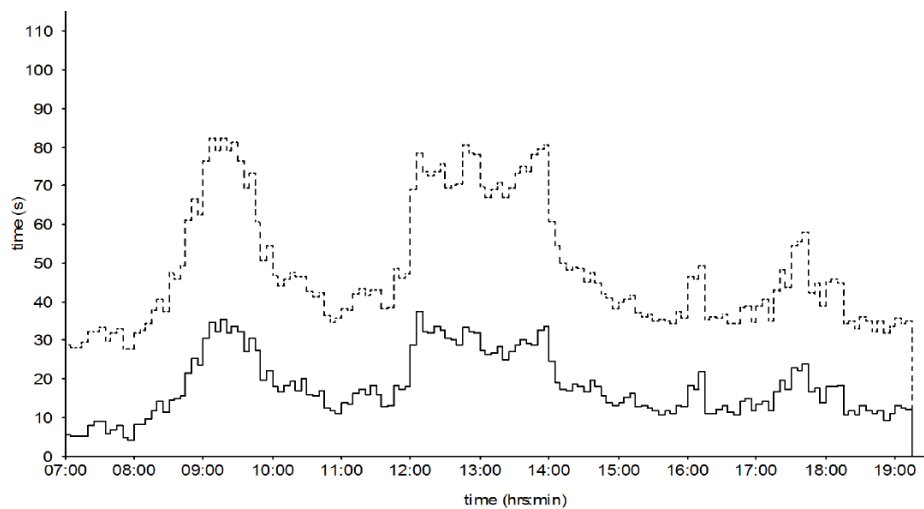
Figure 10 Waiting time (solid line) and time to destination (dotted line) allowing reverse journeys
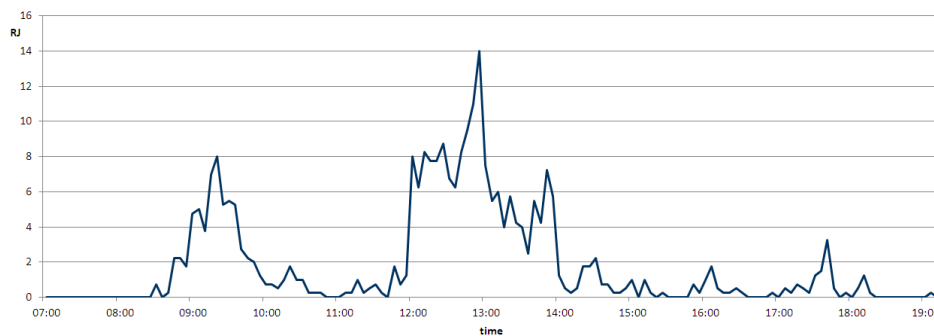
Figure 11 Number of reverse journeys by time of day

Allowing reverse journeys reduces the peak average waiting time (for the worst five minutes) by over 10 seconds. The results also show that reverse journeys are more frequent during busy times.

6   USER INTERFACE

If reverse journeys are allowed the user interface needs to be considered in terms of quality of service [15]. If passenger travel begins in the wrong direction (reverse journey) reassurance indicators reduces the anxiety of passengers and can explain that the reverse journey is not a system fault. Reducing the anxiety will make waits feel shorter [16]. Also the quality of the user interface and the how the information is displayed is important to provide clear information from the lift system. Current displays do not show the stopping order; if they did reverse journeys are easier to understand and are more likely to gain acceptance by the passengers. Suggested formats for displays are given in Figure 12.

Figure 12 Suggested indicator formats to help passengers accept reverse journeys

7 CONCLUSIONS AND FURTHER WORK

Reverse journeys can be avoided with destination control, but only if the system is allowed to refuse calls. Refusing calls is even more frustrating for passengers. Reverse journeys (or longer waiting time resulting from not accepting reverse journeys), are particularly prevalent: (a) with mixed traffic, (b) at peak times, (c) with multiple entrance floors, (d) where not all lifts serve all floor, (e) with restaurants and other busy floors, (f) in under-lifted buildings.

Allowing reverse journeys reduces average waiting time and time to destination, but may confuse passengers. Improved indication can mitigate this problem.

Reverse journeys are not desirable, but sometimes represent the best compromise. Therefore the choice the dispatcher makes whether or not to accept a reverse journey needs to consider more than the optimisation of a combination of waiting and transit time. The acceptance of reverse journeys will be added as a consideration with the dispatcher algorithm to provide improvements in quality of service based on best understanding of the psychology of waiting and travelling in lifts. Future dispatchers will make intelligent decisions about whether or not savings in waiting and transit time justifies the drawback of a reverse journey.

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BIOGRAPHICAL DETAILS

Stefan Gerstenmeyer is a senior engineer at ThyssenKrupp Elevator Innovation GmbH. He has been involved in R&D projects relating to group and dispatcher functions for lift controls. He is a post graduated research student at the University of Northampton.

Richard Peters has a degree in Electrical Engineering and a Doctorate for research in Vertical Transportation. He is a director of Peters Research Ltd and a Visiting Professor at the University of Northampton. He has been awarded Fellowship of the Institution of Engineering and Technology, and of the Chartered Institution of Building Services Engineers. Dr Peters is the author of Elevate, elevator traffic analysis and simulation software.

Lift Books 1890-1940

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Abstract. Most histories of vertical transportation typically examine engineers and inventors, machines and manufacturers, and the architectural and cultural impact of lifts and escalators. However, a critical aspect of this unique history, which has been rarely examined or even considered as having its own "history," is the technical literature of vertical transportation. In fact, this material has a complex history in that it is composed of four distinct bodies of literature: articles published in technical journals, papers published in the proceedings of technical societies, manufacturers' catalogs and commercial publications, and books. The latter category is the subject of this paper.

This paper will provide a survey of books on lifts published in the United States, Great Britain, Germany and Spain from 1890 to 1940. The examination of this international collection of material will reveal a remarkable global awareness of vertical transportation technology during this period. The content of each book will be assessed with regard to its primary topic or focus, organization, illustrations (type, source, etc.), and connections/relationships to other lift books. This paper will provide a critical framework for understanding and assessing this body of material, which may serve in the future as a model for examining other categories of lift literature: articles, papers, and manufacturers' publications.

INTRODUCTION

The fifty-year period between 1890 and 1940 produced the first wave of books on lifts and lift technology. The books published during this period represent a diverse collection in terms of their authors, national origins, publishers, and content. This material is conceptually positioned as one of four distinct bodies of lift literature: articles published in technical journals, papers published in the proceedings of technical societies, manufacturers' catalogs, and books. While the following examination will reveal an occasional blurring of the lines between these categories, the presence of a stand-alone book on a given topic changes our understanding of the material. This is best illustrated by the difference between reading an article in a journal and reading the same text republished in a book. The context of the journal, which includes advertisements, editorials and other articles, coupled with differences in presentation and format, subtly effects our appraisal of the content. The presence of a *book* also indicates that a publisher perceived that a market existed to justify the investment in its production. Thus, the appearance of this body of literature in the first half of the 20th century may be taken as one sign of the emerging field of lift engineering.

THE FIRST LIFT BOOKS 1890 – 1910

The weekly issues of *Le Génie Civil* published between August 29 and October 17, 1896 featured an eight-part series on lifts written by French engineers Georges Dumont & Gustave Baignères. The articles presented an overview of technology that addressed hydraulic, electro-hydraulic, and electric lifts. This approach reflected the marketplace dominance of hydraulic systems and the gradual emergence of electric lift systems. Dumont and Baignères and *Le Génie Civil* may have planned from the start to republish this series and in 1897 one of the first books on lifts appeared:

Les Ascenseurs: Ascenseurs Hydrauliques; Ascenseurs Hydrauliques avec emploi de moteurs à air comprimé, à gaz ou électriques; Ascenseurs Électriques. The full, unedited text of the articles was reprinted, accompanied by the seventy illustrations produced for *Le Génie Civil* (Fig. 1 & Fig. 2).

In 1898 the second book on lifts appeared, however now the setting was the United States and the topic was not technology but law. James A. Webb's *The Law of Passenger and Freight Elevators* offered readers an introduction to the legal issues associated with the installation and use of lifts. Webb published a second edition of his book in 1905, which was almost twice the size of the first edition – a fact that speaks to the litigious nature of American society and the cultural presence of lifts in the early 20th century. 1905 also saw the publication of a book that focused solely on hydraulic lift technology: William Baxter, Jr.'s *Hydraulic Elevators*. Baxter, an American engineer, was a prolific author and his book was primarily a collection of articles written for the *American Machinist* and the *Engineer* and published between 1900 and 1904. However, unlike Dumont and Baignères, Baxter edited and re-wrote several of his articles for the new publication. Produced by the Engineer Publishing Company (Chicago), the book was sufficiently popular to attract the attention of McGraw Hill (New York) and in 1910 they published a revised and substantially expanded edition titled *Hydraulic Elevators: Their Design, Construction, Operation, Care and Management*. Baxter's books are noteworthy for their detailed line drawings of hydraulic lift systems and their broad coverage of the American lift industry (Fig. 3).

The expanded edition of Baxter's book was preceded in 1908 by the publication of Reginald P. Bolton's *Elevator Service* and Ludwig Hintz's *Handbuch der Aufzugstechnik*. Bolton, an English engineer who practiced in the United States from 1894 to 1942, self-published his book, which was the first work devoted to lift traffic analysis. He had developed a series of formulas and charts that were designed to provide a mathematical means and basic theory for determining a given building's transportation needs (Fig. 4). The fact that Bolton's book was self-published makes it difficult to gauge its impact, however the presence of copies in approximately thirty U.S. libraries indicates that it is reasonable to assume that it had a wide distribution. German engineer Ludwig Hintz's *Handbuch der Aufzugstechnik* provides a well-illustrated overview of belt driven, hydraulic, and electric lift systems (Fig. 5). The book also includes a discussion of lift safeties and typical local codes governing lift operation.

The first decade of the 20th century ended with the publication of two small books, both of which prompt questions about their publication history. The first, by American engineer Calvin F. Swingle, was titled *Elevators: Hydraulic and Electric* (1910). The book was described by its author as a "catechism" that included "a thorough drill regarding the construction and care of lifts and their necessary adjuncts," and instruction on "correct, and incorrect, safe, and unsafe methods to be pursued in their operation" [1]. This was an ambitious agenda for a 100-page book that measures only 6.75 x 4.5 inches. However, this little book may have derived from a larger source – its first illustration is labeled "Fig. 380 Otis Traction Elevator." Unfortunately, Swingle did not provide an explanation for this numbering convention and a connection to a larger work (perhaps an encyclopedia?) has not been found. While the second book has a greater page count (174 pages), it is even smaller in size (6.5 x 4.25 inches). Its content also prompts a very different set of questions. Titled *Ascensores Hidráulicos y Eléctricos* and written by Spanish engineer Ricardo Yesares y Blanco, the book was Volume 92 in the Manuales Gallach series (published sometime between 1900 and 1910). The book is a literal translation of Dumont and Baignères' *Les Ascenseurs* – with no acknowledgement of the original authors. It also includes identical and/or slightly re-drawn versions of the illustrations found in the original work (Fig. 6). Yesares did include an additional chapter titled "Nuevos Tipos de Ascensores Eléctricos," three new illustrations (drawings of typical Spanish lift installations), and a brief glossary of terms. This remarkable act of plagiarism appears to have gone completely unnoticed.
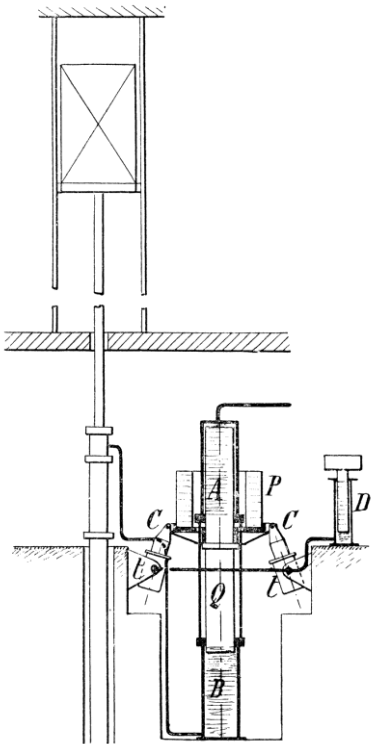
Figure 1 Ascenseur Tomasi. *Les Ascenseurs* (1897).
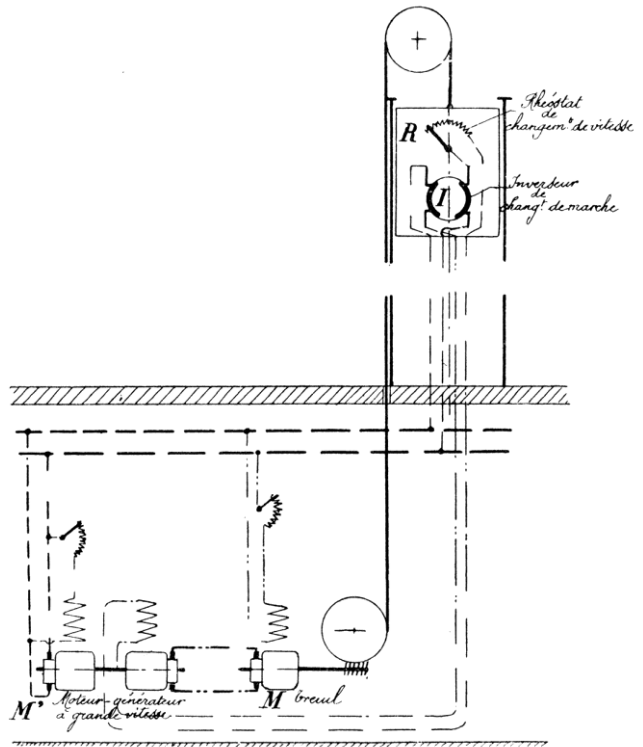
Figure 2 Otis Lift with Ward Leonard Control. *Les Ascenseurs* (1897).
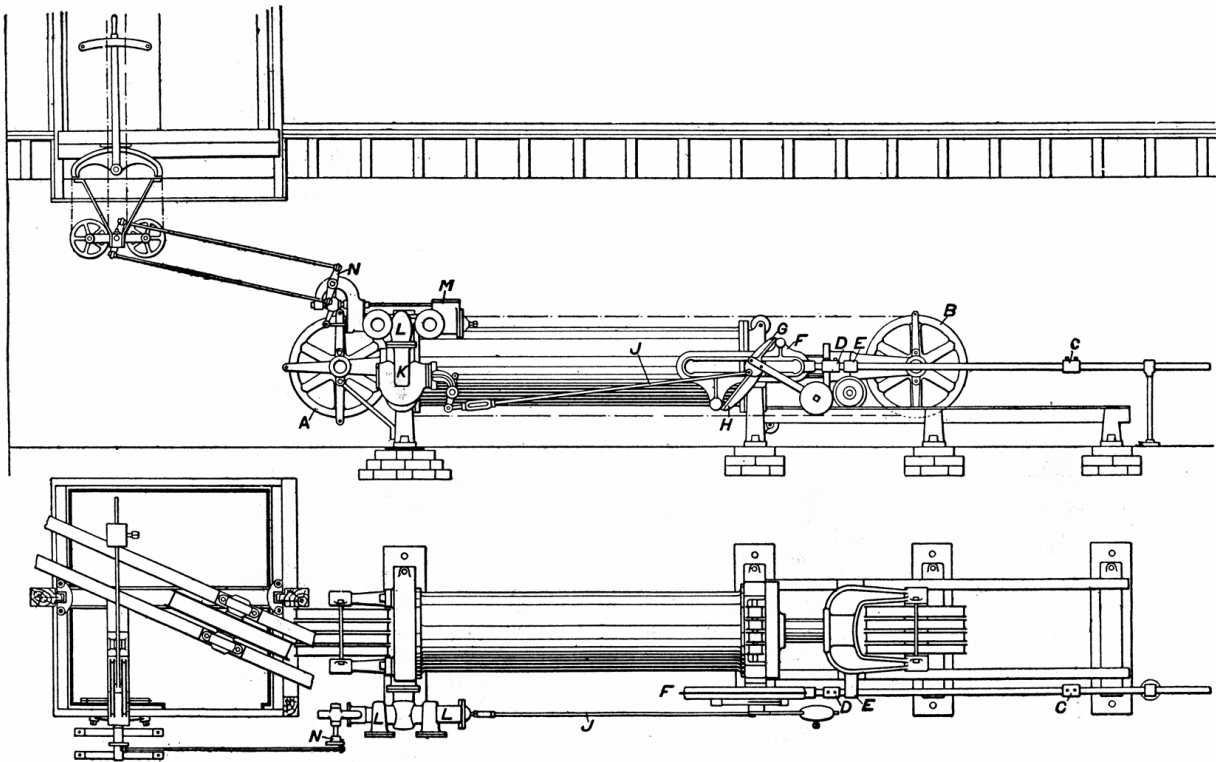
Figure 3 Horizontal Push-Type Hydraulic Engine. *Hydraulic Elevators* (1905).
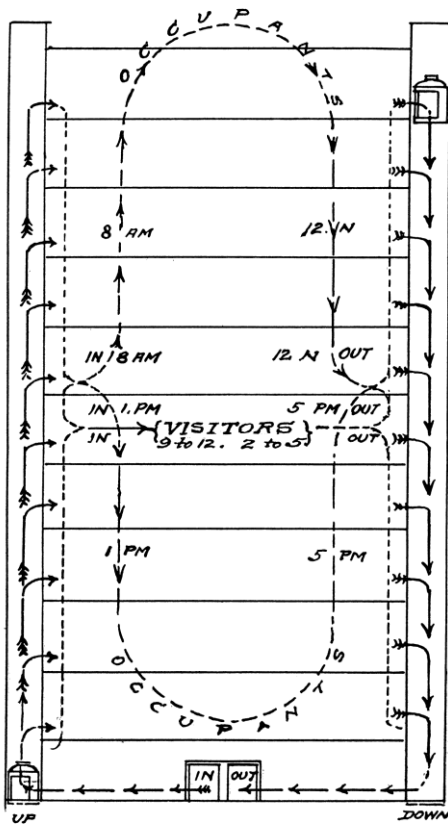
Figure 4 Division of Lift Travel. *Elevator Service* (1908).
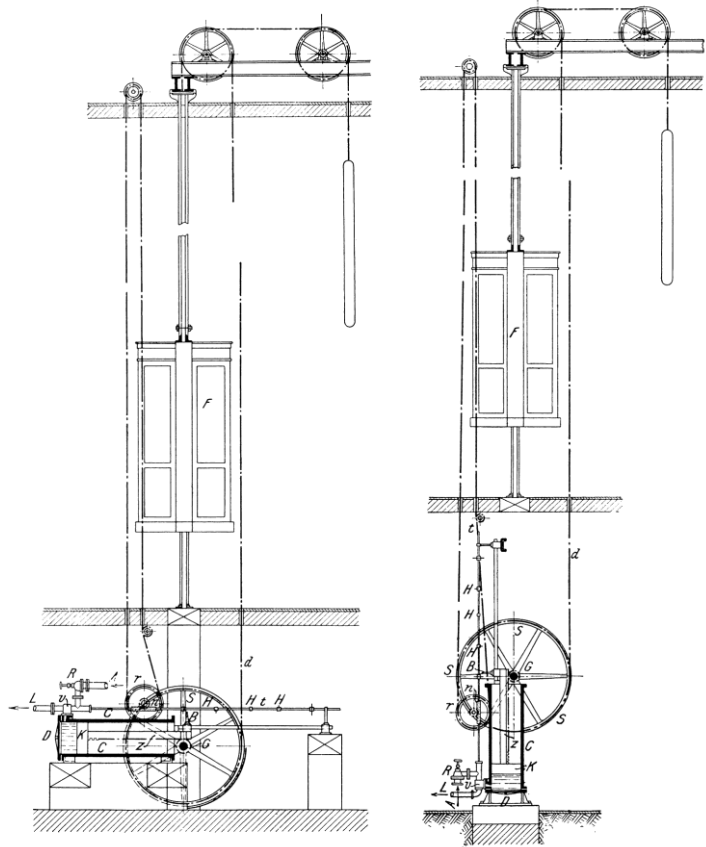
Figure 5 Indirect Hydraulic Lifts. *Handbuch der Aufzugstechnik* (1908).
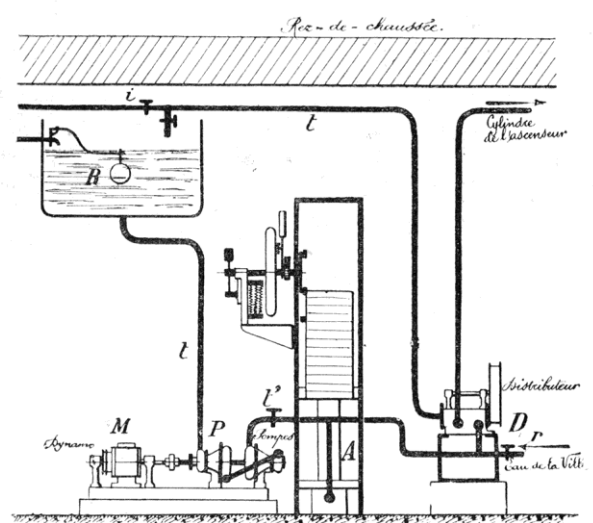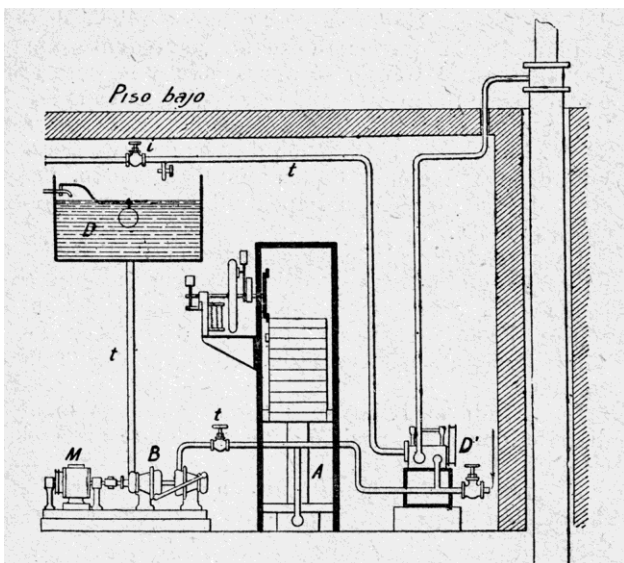
Figure 6 Roux & Combaluzier Hydro-Electric Lift System. Left: *Ascensores Hidráulicos y Eléctricos*, (1900/1920); Right: *Les Ascenseurs* (1897).
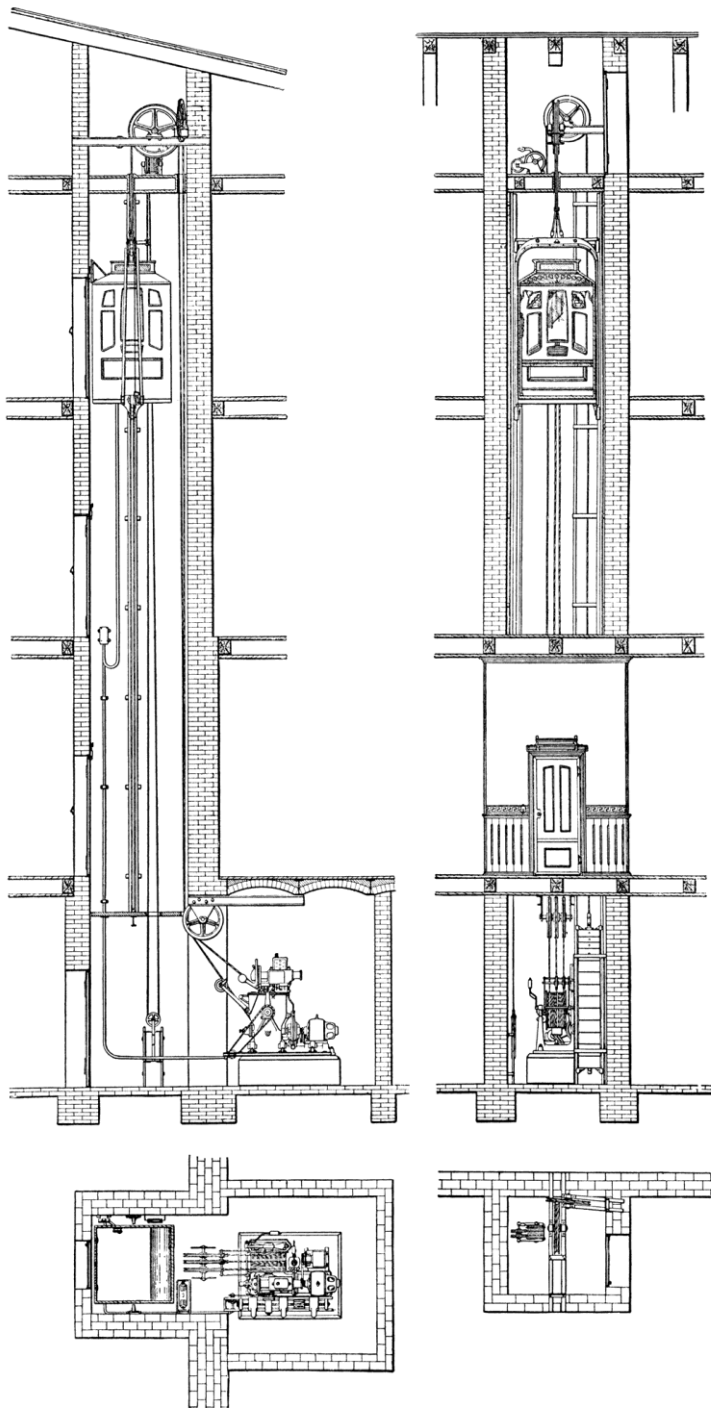
Figure 7 Electric Lift with Push Button Control.
Der Aufzugbau (1913).
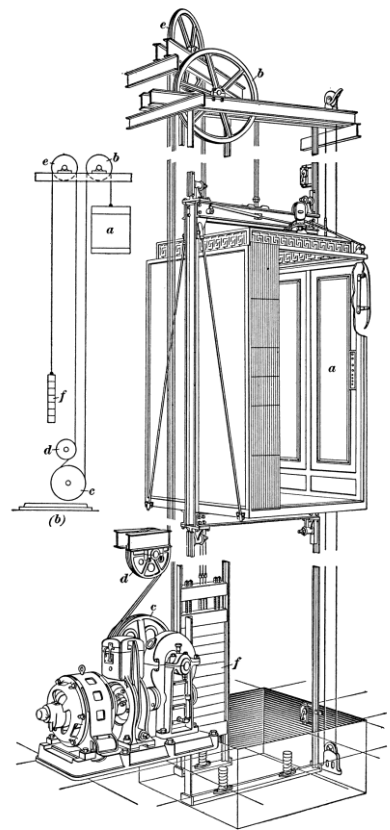
Figure 8 Electric Traction Lift.
Electric   Elevators,   Book   I

LIFT BOOKS 1911 - 1920

The second decade of the 20th century opened with the publication of Hugo Bethmann's *Der Aufzugbau: Ein Handbuch für das Konstruktionsbureau* (1913). This extraordinary book is 720 pages long and features 1,166 illustrations, which include line drawings and black-and-white photographs. Many of line drawings are large scale, fold out illustrations, some of which depict complete system installations (plans and sections) (Fig. 7). The book contains a comprehensive review of lift technology in Germany including hand powered, belt driven, hydraulic, and electric systems. Bethmann provided his readers with a broad technical overview of lift construction and operation as well as an introduction to the science behind the various systems. The book references over forty German companies, five American companies and one Italian company. Somewhat surprisingly the only references to French systems are brief discussions of the hydraulic lifts designed by Leon Edoux and Emile Heurtebise; Bethmann made no references to English companies or English lift systems. This is, perhaps, the most interesting book published between 1890 and 1940. While the text is clearly and precisely written, the illustrations are its most critical asset – they are beautifully drawn, highly detailed, and contain a wealth of information.

American engineers contributed two additional books published during this decade. H. Robert Cullmer's *Elevator Shaft Construction* of 1912 presents a thorough examination of this topic. The publication of this focused study speaks to the increasing complexity of lift systems, which is reflected in Cullmer's 47 illustrations of shaft details. The second book, by John S. Jallings, was similar to Bethmann's in that it offered a comprehensive review of lift types and technology. However, whereas the latter discussed systems from several countries (a discussion admittedly embedded in the context of a distinct national bias), Jallings' *Elevators: A Practical Treatise on the Development and Design of Hand, Belt, Steam, Hydraulic and Electric Elevators* focused exclusively on American developments. The two works were also similar in that Bethmann characterized his work as a kind of textbook; whereas Jallings' book had been initially published as a five-part series designed for a correspondence course on lift technology. These individual works were first published in a single volume in 1915. The first edition was 217 pages long and had 172 illustrations; a second edition appeared in 1918, which was 402 pages long with 278 illustrations. Although Jallings had added content to the book's original chapters, the dramatic increase in its size was primarily due to the addition of a new chapter titled "Equipment Design and Construction," which addressed over 50 separate topics.

LIFT BOOKS 1921 - 1940

Three authors were primarily responsible for the final group of lift books published prior to 1940: Ronald Grierson, Frederick Hymans and Fred A. Annett. In 1923 Chapman & Hall (London) published *Electric Lift Equipment for Modern Buildings: A practical Guide to its Selection, Installation, Operation, and Maintenance*, written by English engineer Ronald Grierson. The book offered readers a thorough overview of American and English lift systems, which was well-illustrated and neatly compartmentalized into twenty-four chapters and seven appendices. Grierson's blending of material gathered from both sides of the Atlantic may have also been strategic – in 1924 the Van Nostrand Company (New York) republished his book in the United States. This new publication differed from the original in three ways: the English edition had included numerous advertisements for lift companies (these were omitted from the American edition); the English edition had included a foldout drawing of a Waygood-Otis electric lift (no similar image accompanied the American edition); and the word *Lift* in the book's title was changed to *Elevator* – no other changes were made.

In 1927 German/American engineer Frederick Hymans and German engineer Axel V. Helborn co-authored *Der neuzeitliche Aufzug mit Treibscheibenantrieb: Charakterisierung, Theorie, Normung*. This was the first book devoted exclusively to traction lifts and the first to focus on the theory

behind this system. While a few prior books had included commentaries on the theory underlying the operation of various lift systems, and a few had included the requisite mathematical formulas, their primary focus had been the operational characteristics of lifts, thus they were primarily illustrated with technical drawings and photographs. In contrast, the majority of Hymans and Hellborn's ninety-nine illustrations feature graphs, charts, and analytical diagrams of discrete lift components. The partnership of Hymans and Hellborn is also curious. The book describes Hymans as a research engineer practicing in New York, while Hellborn is described as a former Engineering Manager for the Otis Elevator Company now living in Stockholm. However, in 1927 Hymans was beginning his 25th year of employment with Otis and Hellborn appears to have only worked for Otis for a short time in the early 1920s.

1927 also saw the publication of the first edition of American engineer Fred A. Annett's *Electric Elevators: Their Design, Construction, Operation and Maintenance*. Annett was an Associate Editor for *Power* magazine and his numerous articles on lifts served as the outline for the book, which addressed all types of American electric lift systems. The book's popularity, coupled with continued rapid changes in lift technology, led to the publication of an expanded second edition in 1935. One of the additions to the revised edition was a chapter titled "Selecting Elevators for Office Buildings," which included formulas and tables that addressed the complex nature of traffic analysis in large buildings. Thus Annett's books, while primarily focused on pragmatic topics, also touched on critical aspects of the science of lift design and operation. These books also featured fewer illustrations and relied more heavily on photographs than earlier works.

During the early 1930s Frederick Hymans continued to write about lifts and the result was a series of short books designed for a correspondence course: *Electric Traction Elevators* (1931), *Elevator Hatchway Equipment* (1931), *Electric Elevator Motors* (1931), *Electric Elevator Operation* (1931), and *Care and Maintenance of Electric Elevators* (1934). These books were published as a two-volume set (*Electric Elevators, Book I* and *Electric Elevators, Book II*) in 1934. These works also primarily focused on electric traction lifts, however they were, in almost every aspect, the polar opposite of his earlier theoretical work. The new books offered readers a pragmatic understanding of traction lifts and are filled, as was the case with similar works, with detailed drawings of lift systems and components (Fig. 8).

The final book published during this period was English engineer Reginald S. Phillips' *Electric Lifts: A manual on the Current Practice in the Installation Working, and Maintenance of Lifts* (1939). This book was, essentially, the English equivalent of Annett's 1935 book, with the focus shifted to the British lift industry. An important difference between the two books was Phillips' explicit reference to the Building Industries National Council's 1935 *Code of Practice for the Installation of Lifts and Escalators*. Phillips' stated that he had adopted, "as far as possible," the terminology found in the Code of Practice and that "most of the safety measures embodied in the code" where "carried into" his book [2]. Although Annett was familiar with the *A17 Safety Code for Elevators Dumbwaiters and Escalators* (the third edition of which appeared in 1931) he made no references to the U.S. code. Phillips' book continued to serve as reference book for lift engineering throughout much of the 20th century: five new editions were published between 1947 and 1973.

CONCLUSION

This brief survey illustrates the diversity of lifts books published between 1890 and 1940, which included general textbooks, specialized technical works, the first book on lift traffic science, and the first book devoted to the technical theories of traction lifts. Of course, to fully appreciate the power of these works they must be studied, read, and compared. This is best accomplished in the "old fashioned" or "analog" method of obtaining information – holding the physical book in your hands and reading the text, taking the time required to carefully fold out and study the larger images, and thumbing back-and-forth between chapters and images. I have the pleasure (and good fortune) of

owning original copies of all but two of the books examined for this paper. The care with which these books were written and illustrated represents the author's and publisher's desire to produce valuable resources for the growing number of lift engineers and other professionals associated with the vertical transportation industry.

A "read" through these books also reveals that, apparently, some things never change. The topics of safety, energy consumption, and lift traffic efficiency were perceived as critical aspects of lift design – much as they are today. There was also a subtle awareness that, perhaps, as soon as a book was published innovations in lift design would render some (or much) of the text obsolete. None-the-less, the importance of these books lies in their preserving the historical record of successful (and failed) ideas, which chart the origins of many of the theories that continue to guide contemporary lift design and operation. Finally, I am well aware, and perhaps even hopeful, that readers of this paper may be quick to note that I "missed" an important book published during this period. Nothing would make me happier than to be able to expand the bibliography provided below and thus enhance my understanding of this important chapter in lift history.

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BIOGRAPHICAL DETAILS

Dr. Gray is the Senior Associate Dean in the College of Arts + Architecture and a Professor of Architectural History in the School of Architecture at UNC Charlotte. He received his Ph.D. in architectural history from Cornell University, Masters in architectural history from the University of Virginia, and undergraduate degrees in architecture from Iowa State University. He is the author of *From Ascending Rooms to Express Elevators: A History of the Passenger Elevator in the 19th Century*. Since 2003 he has written monthly articles on the history of vertical transportation for *Elevator World* magazine. Current projects include a book on the history of escalators and moving sidewalks. He has appeared on the History Channel in *Modern Marvels – Building a Skyscraper* (2004), on PBS in *NOVA: Trapped in an Elevator* (2010) and has been interviewed by BBC 4 Radio – *The Indispensables: Lifts* (2004) and by the BBC World Service – *The Why Factor:* "Why do we behave so oddly inside lifts/elevators?" (2012).

Hybrid Lift Group Control Systems

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Abstract. Over recent years destination control systems have been embraced by all of the major and independent manufacturers having sat at the margins of the industry with only one company actively promoting its use.

As the use of destination systems has risen the known benefits of providing an up peak booster have become a major factor in their being specified. However with the use of destination systems there has been a recognised perception that whilst providing benefits for up peak performance they are not as efficient at handling two way and inter floor traffic. This has resulted in some manufacturers offering hybrid group systems whereby destination control is used to dispatch lifts from the main lobby but uses a conventional two button system to call lifts on the upper floors with active car call buttons to select the destination floor.

This paper compares the efficiency of hybrid systems with dedicated destination control systems across a variety of office building applications. It also looks at the human factors that present barriers to hybrid systems.

1   INTRODUCTION

The purpose of this paper is to try and establish if the use of hybrid systems is more efficient in dealing with two-way and inter floor traffic than destination systems, and if so are there any penalties in terms of service provision. In addition it seeks to explore the barriers and perceptions of building users when confronted with a hybrid system and how these might be addressed.

This paper looks specifically at the use of hybrid group control in modern office buildings and does not consider their application in other environments such as hotels, hospitals and other public buildings.

2   CONVENTIONAL CONTROL

From the outset it should be considered that the use of conventional two button control and hybrid systems have limitations in terms of their application. The main areas of limitations are:

a) For groups of up to 4 cars in a single line. Maximum 8 car group (four cars opposite four).
b) Where all lifts do not serve all floors in the building.

Taking each of the above in turn;

a) Conventional/hybrid systems are really only practical for groups where the maximum number of lifts in a single line does not exceed four. This obviously means that the maximum number of lifts in a group should not exceed eight, four lifts opposite four. With a lobby length of 11.250m, for a 4 car single line of lifts, and a distance between the centres of adjacent lift doors of 2.850m, adding a further 2.7m to the length of the lobby has a significant impact, given the average walking speed of between 1.25m/s and 1.6m/s, see Figure 1. Once you move beyond a line of four lifts crowded lobbies become too long for people to navigate effectively and difficulties arise with accessing lifts within reasonable walking times. This is especially difficult for those with visual and mobility impairment and obviously has an effect on the systems efficiency as door dwell times are increased and lift performance is reduced.

With long lobbies the question of lift arrival indication is also an issue as a more prominent form of signage is required with high levels of audibility for arrival gongs. While flag type or raised direction arrows may be acceptable, highly audible arrival gongs can be obtrusive, especially where lifts open directly into occupied accommodation.

Add to this the undemocratic way in which people access the lifts, i.e. those nearest can board first while those perhaps waiting the longest may be left at the lobby and the limitation become apparent.

b) Where buildings are designed such that not all lifts in the group serve all floors conventional systems may require special landing call buttons and services to cater for passengers travelling to floors served by fewer lifts. In some cases the arrangement is extremely complex, as in figure 2, and it becomes almost impossible to provide an effective service with conventional control systems. Even with less complex configurations there is an adverse impact on lift performance in terms of handling capacity and waiting times to the floors served by fewer lifts. In these circumstances destination systems are far better at managing traffic to such floors.
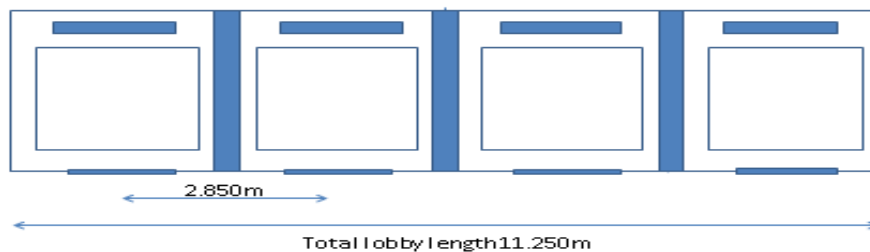
Figure 1

8 Car Group

PL1 PL2 PL3 PL4 PL5 PL6 PL7 PL8

Not all lifts serve all floors

Figure 2

3   DESTINATION CONTROL

The use of destination control as a means of proving improved performance during the up peak period is now well established. With higher saturation points, compared to conventional systems, they are ideal as a 'booster' for the up peak period. These tangible benefits are seen in terms of better passenger management at the main lobby together with shorter journey times and a reduction in the number of stops before reaching the final destination. This all equates to shorter round trip times and increased handling capacity.

All of these features are seen as positives and this has resulted in the use of destination systems as the almost default group control system in large office buildings with multi car groups. All major manufacturers and many third party suppliers of lift control systems now offer destination control as a standard option.

There is however the question that whilst providing an enhanced up peak performance destination systems are not as effective at managing two way and inter-floor traffic. The basis of this is that whilst it is easy to group passengers travelling to the same destination at one point, in the main lobby, this is far more difficult to achieve when passengers are located on different floors and fewer in number. The perception is that longer waiting times are experienced by those passengers moving between floors as the destination system constantly tries to match passengers on different floors to common destinations. The dynamic of upper floor traffic is constantly changing between two way and inter floor and the system needs to be able to respond to these changes while providing the user with an almost instant car allocation.

The ability of some destination systems to effectively manage the dynamics of upper floor traffic, within the constraints of the basic destination template, is difficult. The system is inflexible in terms of call reallocation, something discussed later, and the system constraints limit the ability to provide the most responsive service levels. This leads to a reduction in handling capacity accompanied by increased waiting times.

4   HYBRID SYSTEMS

Hybrid systems appear to offer the best of both worlds, with destination dispatching from the ground floor and the benefits of conventional control in the upper part of the building. With some manufacturers of hybrid systems destination dispatching is available from more than just the main lobby. This arrangement appears ideal for buildings with restaurant, amenity and perhaps function floors located on the upper levels.

One of the key factors and benefits of conventional control systems is the ability to reallocate landing calls. When a landing call is registered the call is allocated to a car that the system computes will provide the fastest response time. If the allocated car is delayed at any point the call can be reallocated to a different lift. While this process is taking place within the group control system the waiting passenger is unaware of any change of allocation and is informed of the lifts impending arrival only when the hall lantern illuminates as the car approaches the floor.

This is in contrast to destination systems where the almost instant allocation of a lift is fixed. Once the passenger is directed to a particular lift then it is expected that the lift will arrive. However if the lift is delayed there is no mechanism to inform the passenger the call has been reallocated. In these circumstances the frustrated passengers tolerance expires and they re-enter their call only to be directed to a different lift or worse, back to the original lift again. This has a negative impact on the user's perception and view of the service being provided and is one of the major difficulties encountered with destination systems.

From the above we can start to see some of the benefits of the hybrid system. Management and grouping of passengers at the main lobby and the elimination of the call reallocation problem on the upper floors, although it should be appreciated this can still happen at the main lobby or any floor where the destination facility is available. However this approach appears to offer the best of both systems and carries a certain degree of logic in terms of a group system operation.

5   HYBRID AND DESTINATION SYSTEMS COMPARISON

In examining the use of hybrid systems it is necessary to try and understand the benefits and drawbacks of each system both technically and in terms of the 'user experience'.

5.1   Destination Control

For:-

- Identifies number of travelling passengers
- Groups passengers according to destination
- Shorter round trip times during the up peak
- Improves waiting time at the main lobby*
- Efficient use of lifts
- Improved up peak handling capacity
- Better allowance for passengers with disabilities (DDA passengers)
- Manages people in the lobbies

* Especially if passenger demand is close to or exceeds handing capacity of conventional systems.

Against:-

- Relies on all passengers entering their destination
- Passengers have no control within the car
- Passengers have to move to the landing to change their destination floor
- Ghost calls reduces efficiency

- Does not signal call reallocation
- Unpopular with some users
- Perceived inefficiencies in handling inter floor traffic
- People try to beat the system – repeated call request or group call function used.

5.2   Hybrid system

For:-

- Identifies number of travelling passengers at the main floor
- Groups passengers according to destination at the main floor
- Provides up peak booster feature
- Manages people at the main lobby
- Good inter floor traffic handling
- Allows space for DDA users from the ground floor.
- Can use hall call allocation on upper floors with heavy traffic (restaurants, meeting floors, etc.)
- Allows call reallocation for lifts responding to upper floor landing calls.
- May carry a cost advantage over a full destination system

Against:-

- May be confusing for users
- Different landing fixtures at ground and other floors
- Car buttons active/inactive at different times
- Not as effective at allowing for DDA use from upper floors
- People try to beat the system. Entering the car and waiting for the COP to become active
- Up to 8 car groups only
- Doesn't know how many passengers are to be transported from upper floors
- Passengers may experience more intermediate stops than destination control
- May not be suitable in groups where all lifts do not serve all floors.

6   SIMULATIONS

In addition to understanding the benefits and drawbacks the relative performance of each system is assessed through simulation in identical applications. The results, using set criteria and performance standards, are set out below for a theoretical building with a typical service requirement.

For the purposes of this paper a 10 floor building of 250,00 sq/ft with a space utilisation of 80% and population density of 1:8m² is considered. Utilisation is the expression of occupied space on each floor with 20% floor space being used for circulation, cabinets, photo copiers, etc.

The selected measurement criteria are:

    a) Up peak traffic

    b) Lunchtime traffic

    c) Two way traffic; 50% incoming and 50% outgoing

    d) Intense inter floor traffic; 10% incoming, 10% outgoing and 80% inter-floor

The two way traffic in 'c' above represents a building with a diversified tenancy where there is no inter floor traffic. Conversely criteria 'd' represents a consolidated tenancy with high levels of inter floor traffic. The criteria used in both 'c' and 'd' is not based on any guidance references but is purely a means of comparing the performance delivery of each system. In both 'c' and 'd' the lifts are operating outside of the up peak and lunch time period.

The performance measurements assessed are Average Waiting Time, Time To Destination and Average Stops per Round trip.

Note - The simulations for up peak and lunchtime are based on the criteria as set out in the Draft BCO 2014 Guide. The profile is constant traffic with a one hour simulation period. All simulations have been carried out using Elevate, Version 8.17 software. For destination control simulations the 'Destination Control (ACA)' dispatcher has been used and for the hybrid simulations the 'Mixed Control (Enhanced ACA)' dispatcher has been used.

It must be recognised that the use of Elevate software provides a set of results that may well be at variance to those achieved by a suppliers own simulations. For the purposes of this paper however the simulation results achieved using Elevate provides the basis of discussion.

The data matrix below details the building and lift criteria applied in the simulations

Building Details

	Area Sq Ft NIA	Sq M	Utilisation 80%	Population 1:8
10	25000	2323	1859	232
9	25000	2323	1859	232
8	25000	2323	1859	232
7	25000	2323	1859	232
6	25000	2323	1859	232
5	25000	2323	1859	232
4	25000	2323	1859	232
3	25000	2323	1859	232
2	25000	2323	1859	232
1	25000	2323	1859	232
Ground				
	250000			2323

Lift data

No of Elevators	SPECIFIED	8
Capacity (kg)	SPECIFIED	2000
Car area (m²)	AUTO	
Door Pre-opening Time (s)	SPECIFIED	0
Door Open Time (s)	SPECIFIED	1.8
Door Close Time (s)	SPECIFIED	2.9
Speed (m/s)	SPECIFIED	2.5
Acceleration (m/s²)	SPECIFIED	0.8
Jerk (m/s³)	SPECIFIED	1.2
Start Delay (s)		0.5
Levelling Delay (s)		0

Results

Traffic Criteria		Control		AWT	ATTD	Stops per round trip
85/10/5 in/out/inter @ 12%	Up peak	Destination		23.3	64.7	3.8
85/10/5 in/out/inter @ 12%	Up peak	Hybrid		22.2	72.8	4.6
45/45/10 in/out/inter @ 13% HC	Lunch time	Destination		30.3	70.5	4.6
45/45/10 in/out/inter @ 13% HC	Lunch time	Hybrid		30.4	81.9	6.3
50/50 in/out @ 13% HC	Two Way	Destination		24.5	62.1	3.5
50/50 in/out @ 13% HC	Two Way	Hybrid		26.6	75.3	5.2
10/10/80 in/out/inter@5% HC	Interfloor	Destination		28.9	62.1	10.7
10/10/80 in/out/inter@5% HC	Interfloor	Hybrid		16.0	46.7	9.2

The results show there is a significant reduction in waiting times and times to destination with a hybrid system when catering for a high level of inter floor traffic.

In the other traffic patterns, up peak, lunchtime and two-way the waiting times are not too dissimilar between the two systems, however the time to destination is longer with the hybrid system as a result of the increased number of stops experienced during the round trip. This suggests that the hybrid is working harder as it is achieving similar waiting times with increased numbers of stops reflecting a higher handing capacity.

The general results show that a hybrid system does mean shorter waiting and journey times for inter floor traffic. The results of the up peak and lunchtime simulations show the destination system performs better in terms of time to destination and fewer intermediate stops while waiting times are similar to the hybrid.

With respect to the passenger's experience of intermediate stops it is important to distinguish between the numbers of stops the lift makes and the number of intermediate stops experienced by each passenger. With passengers entering and leaving the lift at different floors the number of intermediate stops experienced is not the same for each individual. To arrive at the average it is necessary to apply a weighting based on the number of passengers who start the journey together and those who leave the lift at each stop. This will obviously show that the number of intermediate stops experienced by each passenger is different but the average is less than the number of intermediate stops made by the lift. This is an important factor when assessing the 'passenger experience' and is a key element in the marketing of buildings. To effectively arrive at the average number of stops passengers experience it is necessary to track each individual from start to finish of their journey.

The results indicate that hybrid systems are better suited to buildings with a single tenancy where inter floor traffic levels are likely to be higher than perhaps a diversified tenancy building. This obviously poses a question related to the future proofing the building.

7   PROGRAMME MODES

Historically conventional group control systems have sought to manage demand based on responding to the traffic pattern. Up peak, down peak, two way traffic (balanced) have been familiar terms in lift programme language, with the group control system monitoring demand and applying a preprogramed response to the pattern of usage.

The usage was detected by monitoring landing and car calls together with measuring the car load. However the response could be somewhat clumsy and relied on high levels of maintenance to ensure the systems functioned correctly.

This changed somewhat with the advent of lifts working in 'zones' throughout the building. Up peak was retained as a 'programme' to respond to the morning traffic but once this subsided the lifts would revert to a 'zoning' operation whereby the lifts were driven by demand within the zones.

The introduction of microprocessor technology changed the approach to group control whereby call allocation was introduced and greatly improved performance and response times. This was achieved by the use of greater computing power to assess a much wider level of information and to start to match response to demand. Coincident car and landing calls, assessing the 'allocated workload' of each car and knowing accurately the exact position of each car in the shaft allowed systems to operate at a far higher level and provide a much better level of service to building users. 'Relative system response' became a key measurement of performance.

The concept of using different operating modes or programmes is still used in modern microprocessor based systems with the 'up peak' used on conventional systems the most obvious. However the ability of systems to have a completely flexible and seamless response to changing traffic patterns would appear to offer the best solution in terms of system response, given any 'programme' is operating within the parameters of a pre-defined criteria, however flexible that may be. By extension destination systems provide the better means of control given their ability to understand the pattern of demand before passengers enter the lift. This is of course conditional on all passengers entering their destination.

Any destination system, even those working within modes or programmes, is still constrained by the basic principle of the system. This is to group passengers going to the same floors together, whether the demand is for up peak, two-way or inter floor traffic.

8   USER INTERFACES

While the use of hybrid systems provides advantages in terms of waiting times for inter floor traffic patterns the key obstacle is the user's perception of the system based on the interfaces they are confronted with.

The use of different landing fixtures at the main and upper floors together with the car buttons (COP) being active at varying times is perceived as being difficult for building users to understand and comprehend.

There are means of mitigating some of these concerns but if we look at current hybrid systems then we can see that the main issues is with the COP and the points at which it is either enabled or inhibited.

With some current hybrid systems the car operating panel button will illuminate when the destination is selected from the ground floor landing call station. This gives the user the impression the button has been pressed and provides the comfort of knowing the call has been registered and the lift is destined for their floor. In fact all of the car call buttons are inactive and anyone entering the lift who hasn't placed a call from the landing call station is unable to register a car call.

On the upward journey the car buttons are inhibited until the car responds to a landing call. At this point the car panel is enabled and the boarding passenger can register their car call. In theory there shouldn't be a problem with this approach as those who boarded at the main lobby also have their call registration illuminated. However for those people who do not understand the operation of the system, probably the majority, this appears odd and incomprehensible.

To try and address the problem and provide clear indication as to when the COP is enabled/inhibited a better form of indication would appear to be required. One approach could be that the car operating panel is in fact a touch screen. The screen is blank, or carries other information, when the lift is at the ground floor and the 'next stop' indicators located in the lift entrance reveals or floor indicator screen provide the comfort for passengers of knowing they are in the right lift to reach their destination. If the lift stops in response to a landing call then the screen becomes active and illuminates as a conventional operating panel allowing passengers to enter their calls. In this situation it could also show destination floors selected at the main lobby as already 'registered'. In addition the smart use of voice announcements could inform passengers of the status or what to do, 'Your destination has been preregistered', 'Please enter a car call' provide information and may help improve the 'user experience'. There is the matter of DDA access to overcome with touch screens but this approach may be considered less confusing than having something 'not working' such as a set of fixed inoperative buttons.

Clearly there is a need to look at the car panel issue but with people becoming very familiar with the technological approach to so much in everyday life the use of a touch screen in the car, albeit with DDA issues to overcome, may offer a way forward for building users to be less confused.

With landing fixtures there is the opportunity to align the design of the ground floor destination panel with the two button fixture used on the upper floors. These can be architecturally similar in design and have the same configured appearance to the user. The use of either touch screens or key pads should be consistent and be seen by the user as similar.

The use of touch screens, both within the car and on the landings, has major advantages in terms of flexibility especially when considering the use of the lifts with special services such as an Imminent Catastrophic Event (ICE) or fire evacuation. Clear graphic signs and information that is only displayed at the time of use have a significant advantage over fixed signage that is only applicable in certain situations.

Listed below are some of the features a hybrid system could employ to improve the user interface and reduce any confusion.

Overcoming the obstacles:-

- The same style of touch screens or key pads for all landing fixtures
- Touch screen COP that is only illuminated when active
- COP only active for inter floor and main floor travel
- Common graphics for all screens, main landing, upper floors and COP.
- The use of 'smart' announcements.

9   CONCLUSION

The assessment of pure performance shows that there are advantages to hybrid systems in terms of service delivery for buildings with high levels of inter floor traffic. This derives from the increased handing capacity of the system as lifts pick up landing calls in the direction of travel irrespective of the passengers destination.

The case for hybrid systems in the up peak and lunchtime, based on Draft BCO 2014 guidance, is not convincing given the waiting times are similar but the time to destination is longer. This raises the question: is it worth the additional time to destination in the up peak and at lunchtime for the benefits of reduced waiting and travel time for inter floor traffic?

In considering the question it is necessary to factor in the obstacles to be overcome with user interfaces. From the author's visit to an occupied building in Manchester with hybrid systems the

users and facilities management were very comfortable with the systems and how to use them. This suggests that the interfaces did not present a significant barrier to users and that this part of the question is perhaps one of people being adaptable in what they have to do to reach their destination. Refinement of the interfaces would only help to improve the user experience of a system that requires different inputs at different points.

It appears that many people are not comfortable with the fact there are no car buttons with destination systems and that the element of control they had previously is now removed. Couple this to the issues associated with ghost calls, the need for all passengers to register their destination and inability to reallocate calls and a case could be made for hybrid systems in a general sense.

With most of the main manufacturers offering hybrid systems the industry obviously sees they have an advantage in terms of improved service, although one major supplier is stressing that car buttons provide user 'comfort' as part of their marketing approach.

The question of system selection based on performance is subjective based on who thinks what is better; shorter waiting times for inter floor traffic or consistency of user input, notwithstanding the drawbacks of destination systems. Factors such as building tenancy and future proofing could be a major consideration in determining which system is best suited.

From the users perspective the benefits of quicker inter floor service with the hybrid will not be fully appreciated or recognised. The one thing the user is acutely aware of though is waiting time and in the overall performance comparison the hybrid scores better when high levels of inter floor traffic are being catered for.

With ever increasing pressure on buildings to work harder any improvement in lift performance is to be welcomed. Hybrid systems do offer increased performance in one key area and for this reason deserve to be considered.

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BIOGRAPHICAL DETAILS

Len Halsey spent a major part of his career with Otis before joining Canary Wharf Contractors in 1998. Appointed Design Manager for Vertical Transportation Systems in 2002 he is responsible for directing Architects, Consultants and Engineers on VT related design matters to meet Canary Wharf and clients standards. He is a member of CIBSE and holds the post of deputy chair of the CIBSE lift group.

Lift Modernisation the Lost Art of Engineering

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Abstract. This paper investigates the techniques and tools available to the lift modernisation engineer and uses case studies of lift forensic engineering, codes used for imported lifts, reliability impact testing of door systems and ride quality that is achievable. The experienced lift modernisation engineer needs to understand the limitations and design characteristics of the aging lift equipment being considered and how it can be blended in with new engineering components and systems and the original and current code requirements. Also the structural limitations of the building have to be considered for lift equipment removal, routes possibly across floor slabs and the suitability of lift shaft walls for new fixings.

1. INTRODUCTION

"The lift modernisation designer asks, "When is a lift system old?" "When does it require a transplant, brain surgery or a facelift?" in other words, "a modernisation". Lift companies, architects and consultants use various terms to describe a lift modernisation, i.e., conversion, retrofits, renovating, changeovers or upgrading…" [1]

At recent lift conferences and symposia, a high proportion of papers and poster sessions (approximately 30 %) have been devoted to the system approach to lift performance as defined by lift traffic analysis research. The next highest number of papers were devoted to mechanical and electrical design with a bias towards traffic control and green issues. Worryingly all of these papers generally focus on the 'new build' systems rather than the existing lift stock.

According to the published data as of March 2010, there were an estimated 4.5 million units installed within Europe and approximately 207,000 units in the UK [2].

Within the UK there are an estimated 114,000 lift units which were installed prior to 1986 [3]. Depending on the design of the original equipment and how it was maintained, these units may be coming to the end of their useful theoretical design life. The majority of these existing units are in small buildings where, the constraints of a lift modernisation are the existing lift shaft, the size of motor rooms and any equipment which could be re-used, refurbished or modernised.

Within Europe, an estimated 64% of the lifts currently being maintained have been installed in residential buildings and only 14% within offices. Therefore, it appears that a considerable amount of effort and time is being used to carry out lift system analysis on a small proportion of the European lift stock.

When confronted with an existing lift, the majority of lift manufacturers do not consider modernisation as an option for improvement. They prefer to install "standard" units from a catalogue rather than take up the challenge of keeping the old equipment and bringing it back to its original design standard.

In Poland, the existing lift stock is considered to be 81,683 units and it has been estimated that there are over 25,000 units which are 60 years old [4]. These units have had no modernisation and have a

level of original design and craftsmanship that is difficult to achieve today. If Poland decided to replace these historic lifts with new EN81 lifts, it would be considered, and quite rightly so to be an act of historic vandalism.

This does not necessarily reflect on the skills and the expertise of the design engineers and field technicians who specialise in 'new lift installations' but a concern remains that the skills and the expertise of lift modernisation is not being transferred to the younger engineers and technicians employed by companies - consultants, mechanics or technical sales engineers alike.

2. LIMITATIONS

Lift modernisation demands the skills of an engineer with the subtleness of an artist. It could also be described as a technical cookbook where all of the ingredients can be found but unless they are blended correctly in the right proportions the results of the finished lift modernisation could end up being worse than the condition of the system before the works were carried out.

Nowadays, the 'new lift installation' sale transaction is dictated in the form of the standard company product range which has no room for change or compromise because of the way the manufacture and type testing procedures are set up and carried out.

The skilled lift modernisation engineers are not constrained by limitations which come with a new lift installation. They have much more of a "blank canvas" approach towards components or materials which can be used and blended into the scheme design. A good modernisation project has an important advantage; the lift does not lose its character but retains or improves on, important technical and safety aspects from when it was originally installed.

 A savvy modernisation engineer can restore a lift to its original specification and still provide a safe and reliable installation which could outlast a modern lift product from a standard generic range. The older lift equipment has a proven design and manufacturing process, highly reliable and robust components and a high probability of survival. The new lift installations tend to be much more complicated and consist of complex components and sub systems designed to ensure competiveness rather than longevity.

3. MISSION CRITICAL

Just because a lift is "old" it does not mean it has to be unsafe or unreliable. Instead, what has to be considered is whether this lift can fully fulfil its function to transport passengers and goods safely and reliably. Therefore, we have to consider mission critical systems which may require modernisation. These systems include components and sub-systems in the lift motor room, lift shaft, information systems as well as primary safety systems. The mission critical components include, but are not limited to, gearless machines, worm gear drives, controllers, selectors, pulleys, door drives, over speed governors and safety gears.

Just because an individual lift sub-system or component wears out, the total assembly does not need to be replaced. There are specialised manufacturing companies who can and will supply components for old lifts which have the same design and safety characteristics as the original components.

4. FORENSIC ENGINEERING

The modernisation engineer must be aware of code or standard recommendations to reduce energy consumption but should not be restricted by modern technology, traffic handling or aesthetics.

Wooden lift cars with wrought iron enclosures and stained glass decoration, lifts with original machines and mechanical equipment do not need to be mission critical if a sensitive modernisation and restoration process is undertaken. Since a standard modern lift typically cannot be sensitively blended into an historic environment, a modernisation engineer should utilize the tool of forensic engineering.

Forensic Engineering is considered to be the 'investigation of materials, products and structures of components which have failed or do not operate or function as intended thus causing damage, consequently the Forensic investigation aims to locate causes of failure with a view to improve performance or extend the life of a component'.

In the lift motor room the components considered to be mission critical are the motor and gearbox assembly as well as controller. There may also be an over speed governor which could be "old" and not up to the current code requirements. However, as long as it operates in accordance with the code applicable at the time of installation it should match with the safety gear installed.

When considering the geared or gearless machines, some even older than 50 years, the simple option would be to remove them along with any associated problems and blending the new equipment with the existing structural steel bedplate. This would require a structural analysis of the original bedplate plate design as the new equipment load paths could vary dramatically from the existing structure. The new arrangement, however, will very likely deflect causing premature failure of the new equipment. On the other hand, if modernisation is considered the equipment load paths would remain the same requiring reduced design development and lower capital costs making it a much more cost effective solution.

It is very difficult or nearly impossible to visually inspect the internal components of a worm geared traction machine and give an assessment of the expected remaining life expectancy for the unit [5]. In such case, it is recommended that a Forensic Engineering survey is carried out on the unit(s)

A considerable amount of information can be obtained from the analysis of the oil and grease taken from the gearbox reservoir and bearing housings. Also non-destructive testing techniques could be undertaken such as thermal imaging on bearings.
The alternative means of extracting such information would require destructive testing or sending the unit back to the original manufacture [5], assuming they are still in business.

The oil analysis report provides specific site inspection information and an estimation of the oil condition by detailing its state, presence of any additive elements and an elemental analysis of the oil contamination by potential wear metals.

Table 1 Example of the oil sample analysis

An No.	Sample Date	Oil Condition												Additive Elements ppm				
		Visc. 40°C	Appearance	Disper-sancy	Water	Glycol	Fuel	Initial pH	TAN	Oxida-tion	TBN	Ferrous Debris	ISO	Ba	Ca	Mg	P	Zn
1	19/01/09	288	70	n/a	N	n/a	n/a	n/a	n/a	n/a	n/a	90	n/a	2	6	2	304	22

An No.	Sample Date	Elemental Analysis - Contamination & Wear Metals ppm																
		B	Na	Si	Li	Al	Cr	Cu	Fe	Pb	Sn	Mo	Ni	Ti	Ag	Mn	V	Oil Chg	Oil Age
1	19/01/09	1	< 1	7	< 1	< 1	1	566	181	26	71	1	4	< 1	< 1	2	< 1	Y	-1

An example of such an analysis (Table 1) shows that the oil sampled was either replaced at some point or contaminated with an unsuitable grade or the lubricant has deteriorated over time. The forensic investigation showed that fairly significant levels of ferrous debris were present. Further investigation showed that the "A" bearing had failed (Sketch 1) – such detailed information could not have been obtained from a visual inspection or without dismantling the machinery.

Sketch 2 Sectional Perspective of a Single Worm Geared Machine [1]
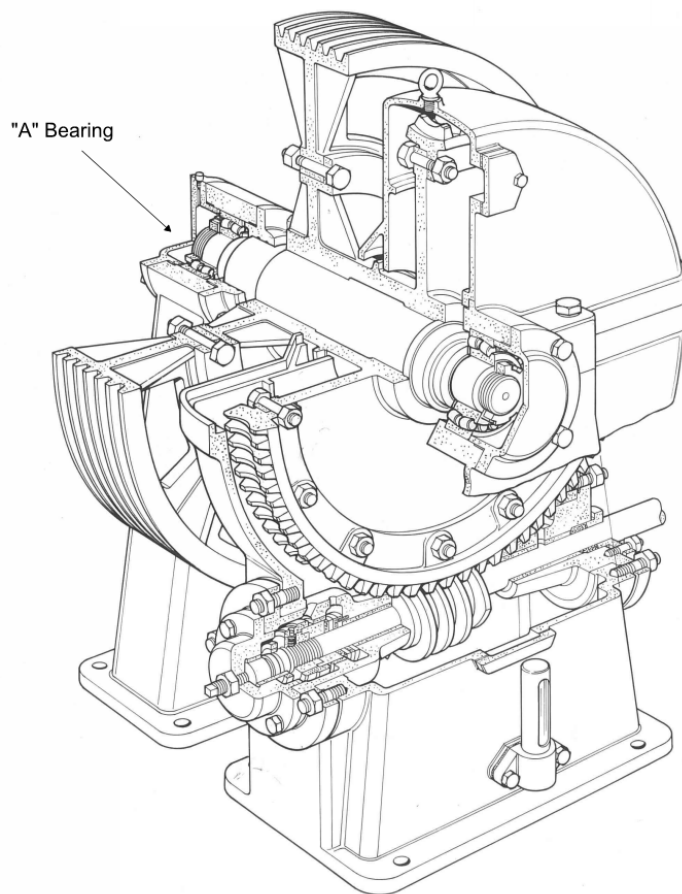
The forensic analysis also showed high levels of 'wear metal' elements (Copper -Cu and Tin -Sn) in both samples – these 'wear metals' originated from the sliding friction between the phosphor bronze

worm wheel and the worm shaft as well as from the shaft rotation in the plain sleeve bearings. These characteristics are typical for the traditional worm and wheel traction lift winding units.

The Elevator Vibration Analyser is a tool that also can be classified as a forensic aid which can be used to determine the condition of a component. It is well known that lift noise and vibration analysers are used to determine limits of noise and vibration within a moving lift car, but they can also be used to determine where the noise and vibration originate from. The source could be the machinery, the ropes, the pulleys, the guide rails or even the guide shoes. Lateral quaking, is for example, the horizontal swaying of the lift car and can be caused by bends in the guide rails and/or inadequate operation of the roller or sliding guide shoes. Vertical vibrations mainly originate from the hoist machine or the pulleys. It is transmitted though the ropes and it can potentially occur due to the dynamic balancing of the drive motor. The acceleration, deceleration and jerk, in turn, give the passengers a sensation of their weight increasing or decreasing, and can be a result of the lift sticking to the guide rails due to high pressure and/or high friction.

5. MAINTENANCE

The first truly modern use of electronics in the lift controllers took place in the 1970's. Before this date, the controller was referred to as "relay logic" and was both generally simple and reliable. For office buildings however this type of controller did not have the quick response time demanded by the lift system engineers for the traffic patterns occurring in new office buildings. Also, this control system did and still does suffer when installed in a "dusty" environment which has been made worse by lift maintenance companies reducing the time spent performing routine maintenance and adjusting the relays.

These relay logic switches are still very common and are easily maintained and repaired. Moreover, if quick electronic response times are not required, there is no real reason why they cannot be incorporated into an historic lift modernisation ahead of a new microprocessor based lift controller. Unfortunately, a less experienced lift modernisation engineer will likely opt for the easy replacement option, probably due to the skill base focused on modern technology rather than maintain and adjust the old lift.

The maintenance company's approach to the allocation of time and resources for routine maintenance has recently been typically centred around new complex lift technology. As a result, the time allowed for each maintenance visit has been reduced to a minimum and it is now insufficient for proper lift care, possibly preparing the customers for new lift sales driven by the existing lift reliability issues.

6. A DIFFERENT APPROACH TO MODERNISATION

The continuing upkeep and maintenance of the 25.000 historic lifts in Poland suggest that it is possible to preserve a higher skill base which encourages the re-manufacture of components to match their original design and specification. This also suggests that the engineers and architects understand the social need for modernisation.

Poland has one of the largest skill bases which are actively pursuing the modernisation of old and historic lifts, with approximately 32% of these lifts running over 60 years. This is no reflection on the skill of the younger lift engineer, but a living proof that there is a room for both, the restoration engineers and the standard new installation lift engineers within our industry.

7. CODES, STANDARDS AND GOOD PRACTICE

It is only in relatively recent times that codes and good practice guidelines for lifts have been published. In the UK, British Standard 2655: Part 3; 1971 [6], sets out the recommended arrangements for standard electric lifts in metric units. Prior to this date, the units for manufacturing, installation and buildings were in the imperial measurements of feet and inches. (Note: British Standard 2655: Part 3; 1971 was superseded in 1989 and replaced by EN81-3:2000+A1 2008 [7].)

This date is important to the original understanding of design limitations of lifts installed in the UK. The lifts could have originated from a British manufacturer, a European supplier, or in the case of prestigious, relatively tall buildings at the time, from the USA which although using imperial units of measurement, would use American standard screw threads which would be not compatible with the British Standard screw threads or spanners.

Prior to the European Lift Directive being put into practice there had been lift installations fully imported from Japan, for example. In these instances, the code of manufacturing and component design had followed the Japanese Standard (JIS). These lifts will require modernisation in the near future. Consequently it has to be assumed that the components of these installations will have different design characteristics to those of the modern components, thus requiring a detailed site investigation and inspection of all components for wear, damage and proper installation.

Another example of conflicting codes is a situation where a lift guide rail has a 'bend' which has probably been there since installation and needs to be replaced. The modernisation engineer is faced with a decision whether or not to remove the damaged rail and lower the sections above the damaged section so the keyways slot into place as they have the same design characteristics. What specification should the new rail be? Should it be to ISO 7465:2007, was it a British Guide Rail with imperial dimensions, an A17.1 or JIS standard?

It is still possible to find lifts with wooden or round car or counterweight guide rails which although not modern code compliant, have probably given over 60 years of reliable service while correctly matched with a compatible safety gear. Removing and replacing this type of guide rails with modern Tee section guide rails would require a full structural assessment of the shaft walls, as well as possibly a new car sling and car.

In the majority of instances re-fixing or repositioning of lift guide rails in an old lift shaft, which were mainly constructed in masonry, can be a real design challenge not only for the guide brackets but also door frames as the existing construction cannot always be properly identified and assessed.

The lift modernisation engineer, when confronted with shaft walls of unknown construction, has several design options depending on the possible fixings being considered. In any case loading tests should be carried out on site, where a load application device is used to test the masonry to see if it detaches from the bond.

8. FINAL THOUGHTS

Just because a lift is being modernised, it does not mean that it cannot comply with the requirements of universal access. Although the physical size of the lift can have an effect on full lift compliance and the repositioning of the car operating stations can destroy the architectural features of wooden decorative lift cars, the introduction of a modern LCD indicator would be totally out of character with the old lift. Therefore, the lift modernisation engineer must not only be a skilled engineer who understands the limitations of the lift being modernised but also must be aware of the options

available and understand which components can be overhauled or remade. Probably the most important virtue they must possess is to be a sympathetic lift conservationist, so that the specified modernisation works do not end up being nothing more than historic vandalism.

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BIOGRAPHICAL DETAILS

The Authors would like to thank all colleagues at ARUP for all their advice and assistance and more importantly their enthusiasm for promoting the modernisation of lifts.

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Computer Simulation Model of a Lift Car Assembly with an Active Tuned Mass Damper

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Abstract. In engineering systems a Passive Tuned Mass Damper (a secondary mass – spring - damper combination) is often used to reduce vibrations of a primary structure (main mass). In an Active Tuned Mass Damper (ATMD) arrangement vibrations of the main mass are attenuated when the secondary mass (referred to as an active mass) is actively controlled. The ATMD system is equipped with a controller, sensors and an actuator. The attenuation is achieved by the application of control force determined by a suitable feedback control algorithm. In this paper the ATMD method is considered to attenuate resonance vertical vibrations of a lift car assembly – suspension rope system during the lift travel, when the frequency of harmonic excitation acting upon the car assembly becomes near its natural frequency. A mathematical model with the optimal feedback gain calculated using Linear–Quadratic Regulator control law is developed. Then, a case study is presented in which computer simulation is carried out. The simulation results are discussed and the effectiveness of an active tuned mass damper system is demonstrated for a given set of lift system parameters.

1   INTRODUCTION

Excessive vibrations in a lift system compromise car ride quality and may lead to wear, fatigue, malfunctioning, failure and structural damage of the installation. The underlying causes of vibration are varied, including poorly aligned joints and imperfections of guide rails, eccentric pulleys and sheaves, systematic resonance in the electronic control system, and gear and motor generated vibrations [1]. In high-rise applications lifts are subject to extreme loading conditions. High-rise buildings sway at low frequencies and large amplitudes due to adverse wind conditions and the load resulting from the building sway excites the lift system. This results in large vibratory motions of lift ropes [2,3].

Vibration suppression (reduction) can be achieved through *passive*, *semi-active* and / or *active* control methods. In passive control the aim is to develop a design of the system in which amplitudes of vibration are limited through an optimal choice of mass, stiffness and damping characteristics. However, often the desired level of vibration reduction cannot be obtained by passive methods and in order to achieve high performance of the system active vibration control (AVC) strategies must be applied [4]. In active vibration control a set of actuators with external power supply is used to provide a force to the system in order to limit vibration amplitudes. In this approach a set of sensors and a suitable control algorithm (feedback/ feedforward) are used to determine the control force to be applied. For example, in lift systems an active vibration damper can be applied under the lift car, fitted between the floor and sling, to suppress its vertical vibrations [5].

In resonance conditions (when a structure is acted upon by a force whose frequency coincides with its natural frequency) vibration attenuation can be introduced by the application of an auxiliary spring – damper - mass combination (a dynamic vibration absorber) attached to the main structure (primary mass). The best vibration control effects are then achieved when the mass – spring –

damper parameters are optimally tuned. Thus, this implementation the absorber device is referred to as a *tuned mass damper* (TMD).

In order for the TMD to be effective the harmonic excitation should be well known and its frequency should not deviate from its constant value. If the driving frequency drift occurs or there are changes in the TMD characteristics, the tuning condition will not be satisfied and the primary mass will experience some vibration. Furthermore, the driving frequency might be shifted to one of the natural frequencies of the combined primary – secondary mass assembly and the system will be driven to resonance and potentially fail. In order to address these issues a semi-active or active TMD device can be applied.

In this paper the concept of active tuned mass damper (ATMD) is discussed in the context of lift applications. The principle of operation and an ATMD is explained and then its operation is demonstrated through a case study involving a lift car-suspension model subjected to resonance vibrations.

2   ACTIVE TUNED MASS DAMPER

Fig. 1 shows a schematic diagram of a structure equipped with an ATMD system. Vibrations x_1 of the main mass m_1, acted upon by an excitation force *f(t)*, are attenuated by the application of an actively controlled auxiliary mass m_2. The ATMD system is equipped with a controller C_o, sensors s_1, s_2 (typically accelerometers) and an actuator providing a control force *u(t)*. The active attenuation is achieved by the application of control force *u* determined by a suitable feedback control algorithm.
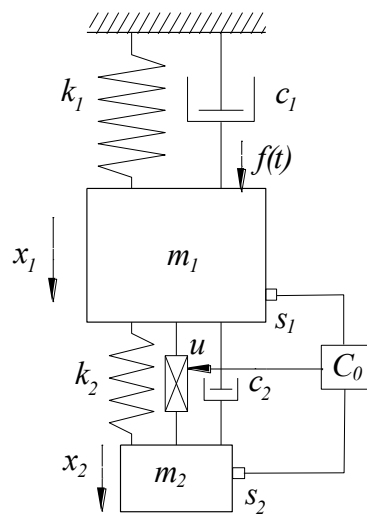
Figure 1 Schematic diagram of a structure equipped with an ATMD system

By introducing the state variable vector $\mathbf{x} = \left[x_1, x_2, \dot{x}_1 \; \dot{x}_2 \right]^T$, where x_1 and x_2 represent the absolute displacements of the main mass and the auxiliary mass, respectively, and the overdot denotes differentiation with respect to time *t*, the equations describing the dynamics of system can be written as [6]

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}_u u(t) + \mathbf{B}_f f(t) \tag{1}$$

where the matrices **A** (the state matrix), $\mathbf{B}_u$ (the input matrix) and $\mathbf{B}_f$ are defined as follows

$$\mathbf{A} = \begin{bmatrix} \mathbf{0}_{2x2} & \mathbf{I}_{2x2} \\ -\tilde{L} & -\tilde{C} \end{bmatrix}; \quad \mathbf{B}_u = \begin{bmatrix} 0 & 0 & -\dfrac{1}{m_1} & \dfrac{1}{m_2} \end{bmatrix}^T; \quad \mathbf{B}_f = \begin{bmatrix} 0 & 0 & \dfrac{1}{m_1} & 0 \end{bmatrix}^T \tag{2}$$

with the mass-normalized stiffness and damping matrices $\tilde{L}$ and $\tilde{C}$ defined as

$$\tilde{L} = \begin{bmatrix} \dfrac{k_1 + k_2}{m_1} & -\dfrac{k_2}{m_1} \\ -\dfrac{k_2}{m_2} & \dfrac{k_2}{m_2} \end{bmatrix}; \quad \tilde{C} = \begin{bmatrix} \dfrac{c_1 + c_2}{m_1} & -\dfrac{c_2}{m_1} \\ -\dfrac{c_2}{m_2} & \dfrac{c_2}{m_2} \end{bmatrix} \tag{3}$$

where c_1, c_2 and k_1, k_2 are the coefficients of damping and stiffness, respectively. In a state feedback approach the control force is determined as $u(t) = -\mathbf{G}\mathbf{x}$, where $\mathbf{G} = \begin{bmatrix} g_1 & g_2 & g_3 & g_4 \end{bmatrix}$ is a gain vector. The output equation is then given as $\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t)$, where the constant output matrix is $\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}$. The closed-loop control system can then be represented by the block diagram shown in Fig. 2.
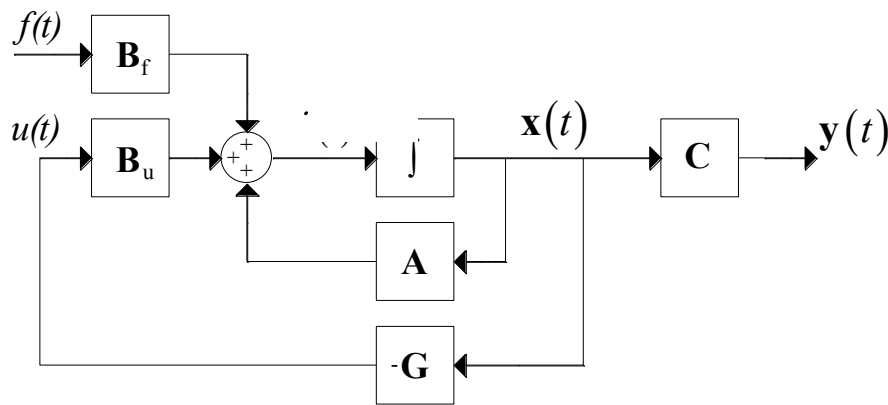
Figure 2 Closed-loop control system.

The most effective and widely used technique to determine the gain vector $\mathbf{G}$ and to obtain an asymptotically stable control system is the optimal Linear Quadratic (LQ) regulator [4]. This technique involves minimizing the cost functional (the quadratic performance index)

$$J = \int_0^\infty \left(\mathbf{x}^T \mathbf{Q}\mathbf{x} + Ru^2 \right) dt \tag{4}$$

in order to determine the control u, where $\mathbf{Q} = diag\begin{bmatrix} q_1 & q_2 & q_3 & q_4 \end{bmatrix}$ is the state cost matrix (with time invariant weights), and R is the control force weight. According to the LQ theory the optimum control law is then expressed as:

$$u(t) = -R^{-1}\mathbf{B}_u^T \mathbf{P}\mathbf{x} = -\mathbf{G}\mathbf{x} \tag{5}$$

where $\mathbf{P}$ is the solution of the Algebraic Riccati Equation (ARE, [4]).

3   LIFT MODEL

A lift car assembly – suspension rope model is depicted in Fig. 3. The combined mass of the assembly, denoted as M, is suspended on ropes of length L and mass per unit length m_r each (see

Fig. 3a). Fig. 3b shows a single-degree-of-freedom (SDOF) vibration model representing the fundamental vertical (bounce) mode with the overall motion denoted as x_c. In this mode both the car and sling move in phase and the effective modal mass is then determined using the kinetic energy expression corresponding to the vibration mode. The equivalent (effective) mass is given then as $M_e = M + {}^{n_r m_r L}\!/\!_3$, where n_r is the number of ropes. The flexibility of ropes is represented by a spring of effective coefficient of stiffness given as $k_e = n_r {}^{EA}\!/\!_L$, where EA is the product of modulus of elasticity and cross-sectional area of the ropes. Damping in this model is represented by a dashpot damper of the effective coefficient of viscous friction c_e.
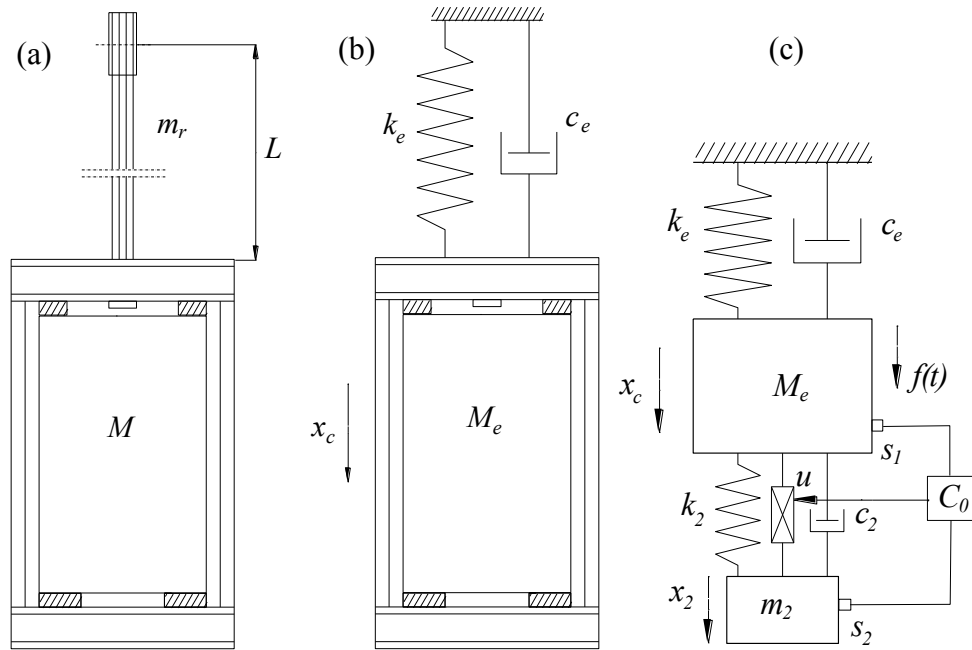
Figure 3 Lift car – suspension rope model.

Following what has been discussed above the application of ATMD can be considered to reduce vibrations of the car assembly. In schematic diagram shown in Fig. 3c an actively controlled auxiliary mass is fitted under the sling to implement the ATMD strategy.

4   NUMERICAL SIMULATION: CASE STUDY

The performance of an ATMD is demonstrated through a numerical simulation experiment. In the simulation the lift travels at rated speed $V = 2$ m/s. The car - sling mass is $M = 1400$ kg and the assembly is suspended on $n_r = 4$ steel wire ropes in 1:1 configuration. The ropes are of modulus of elasticity $E = 0.85 \times 10^5$ N/mm^2, mass per unit length $m_r = 0.66$ kg/m and effective area $A = 69$ mm^2 each. A scenario in which the car is subjected to harmonic excitation $f(t)$ of frequency 3.7 Hz is considered in the test. The frequency of excitation becomes tuned to the natural frequency of car – suspension system during the lift travel when the length of the suspension ropes L is 30 m (see Fig. 4a). This results in resonance at the time instant of about 11.25 s and without application any active mitigation measures the car will suffer from excessive vibrations (with peak-to-peak displacements of over 3.4 mm, see the resonance region identified in Fig. 4b).

However, if ATMD is used and tuned according to possible resonance scenarios vibrations can be substantially reduced. In order to mitigate the effects of resonance in the above scenario, the lift performance is simulated when the car assembly is fitted with an ATMD system with moving mass $m_2 = 71$ kg equipped with an actuator capable of providing the maximum force of about 50 N,

dictated by LQR algorithm. The damping ratio of the car – suspension system is assumed to be $\zeta_e = 5\%$ and the optimal value of damping ratio of the ATMD system is determined as $\zeta_2 = \sqrt{\dfrac{3\mu}{8(1+\mu)}}$, where $\mu = \dfrac{m_2}{M_e}$. The coefficient k_2 is determined as $k_2 = \dfrac{m_2}{1+\mu}\sqrt{\dfrac{k_e}{M_e}}$ [7]. The performance of the system is illustrated in Fig. 5.

(a)

(b)
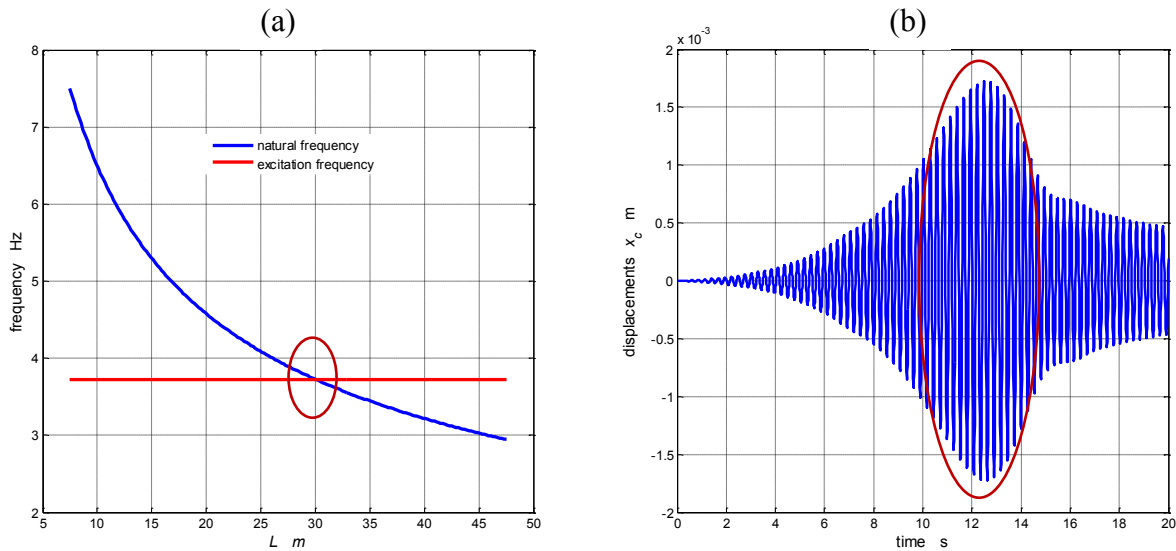
Figure 4 Lift resonance.

(a)

(b)
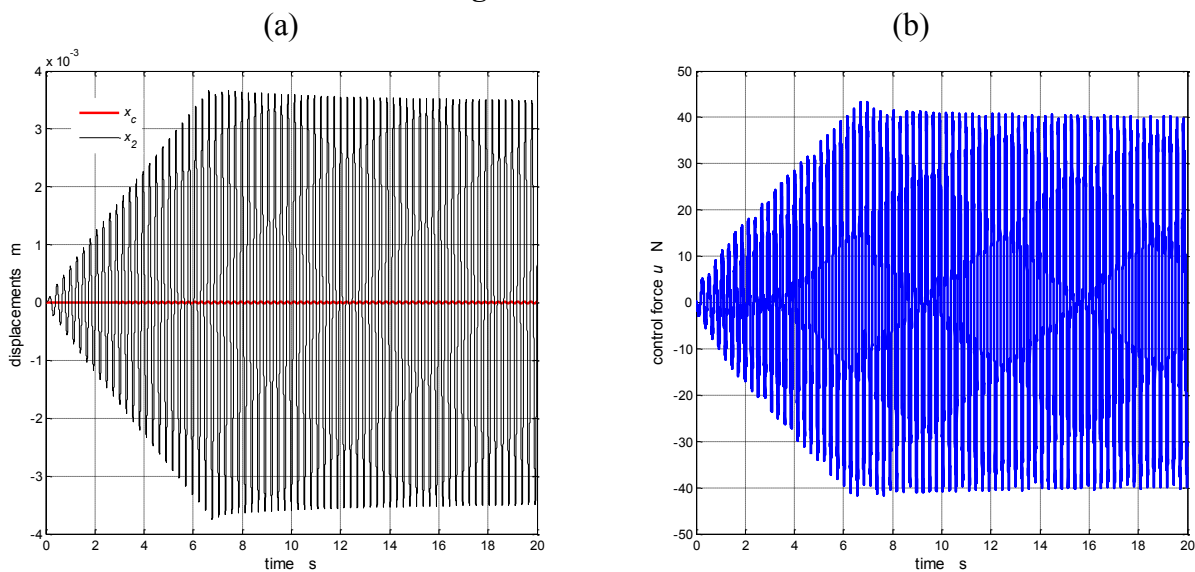
Figure 5 (a) Displacements of the car (red line), active mass (black line) (b) control force.

Fig. 5(a) shows that with the actuator providing a control force of t magnitude about 40 kN and the active mass peak-to-peak displacements of about 7 mm, the car vibrations can be eliminated. The results of numerical experiments will be illustrated with co-simulation and visualization using a model developed in a multibody system dynamics software environment and Matlab/ Simulink.

5   CONCLUSION

In a lift installation an adverse situation arises when one of the time-varying natural frequencies of the car – suspension rope system becomes near the frequency of a periodic excitation existing in the

system. This results in a passage through resonance. In such a case the lift car will not vibrate throughout its travel, but will pass through a resonant vibration at some particular stage in the travel. Passive vibration isolation techniques are often applied to mitigate the effects of resonance. However, active vibration control methods can be used to control adverse dynamic behaviour of a lift. For example, resonance vibrations of a lift car can be attenuated by the application of a suitable ATMD system, as demonstrated by the results of numerical experiment carried out for a given set of lift system parameters.

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BIOGRAPHICAL DETAILS

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The Calculation of Stress Distribution of Big Rope Sheaves

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Abstract The aim of this paper is to analyse the load conditions (pressure between rope and sheave) and the stress distribution of large sheave systems. Both an analytical model for calculation of contact forces between rope and sheave was developed as well as extensive theoretical and experimental tests were realized to determine the load and stress situation of big sheaves.

A practical numerical model based on a parameter assisted multi-body simulation model for the simulation of the dynamic run of a rope over a sheave was developed. The outcomes of this are the following findings.

By small wrap angles (smaller than 60°) the peaks of the line contact pressure go partially or completely together when the rope enters onto and runs of the sheave and this results in a noticeable higher contact force, which was unknown so far. Within the analysed rope constructions there are maximum forces of 6 times of the constant (so far considered for the dimensioning of sheaves) part of the line contact pressure by small wrap angles.

Also the rope forces and pressure load acting on sheaves due to acceleration forces during start-up process or rundown of conveyor systems, and the pressure due to a fleet angle between rope and sheave, were looked at with this multi-body-system. Finally, in the research study a method for the calculation of the load of sheaves was developed based on the finite-element-method for the calculation of the deformations and stresses of the sheave.

The verification of the developed calculation and simulation methods could be done successfully by a sheave of a rope way used in practice. Consequently, the results of this research study provide fundamental guidelines for the design of big sheaves in lifting applications.

1 STATE OF THE ART AND RESEARCH

Up to now, it was assumed that for strength calculation and dimensioning of sheaves (Fig. 1) the line contact pressure (normal force) between rope and sheave is constant [1]. But when the rope enters onto or runs off the sheave the line contact pressure increases because of the bending stiffness of the rope [2]. These peaks can reach up to 4 times of the average line contact pressure, which depends on rope construction, rope force and ratio of diameters between rope and sheave. Furthermore there are more influencing factors unconsidered as for example lateral forces because of fleet angles or dynamic forces because of start-up processes and rundowns of conveyor systems.

So far, due to low computing power, the strength calculation (deformation and mechanical stress) of sheaves could only be done by highly simplified models of the sheave and with the help of frame analysis programs. With this method a detailed model of the sheave e.g. containing welds and screw couplings is impossible. So the internal stress situation of sheaves could not be calculated completely up to now.

Figure 1 Sheaves of a ship lift

2   PRESSURE BETWEEN ROPE AND SHEAVE - ANALYTICAL MODEL

Both, an analytical model for calculation of contact forces between rope and sheave was developed, as well as extensive theoretical and experimental tests were realized to determine the load and stress situation of big sheaves.

The basis for calculation of constant part of the line contact pressure q was an existing analytical model (Eq. 1) with the rope force F and the radius of the sheave R_0 [3].

$$q = \frac{F}{R_0} \tag{1}$$

This calculation method was extended with the mass and the velocity of the rope (Fig. 2).
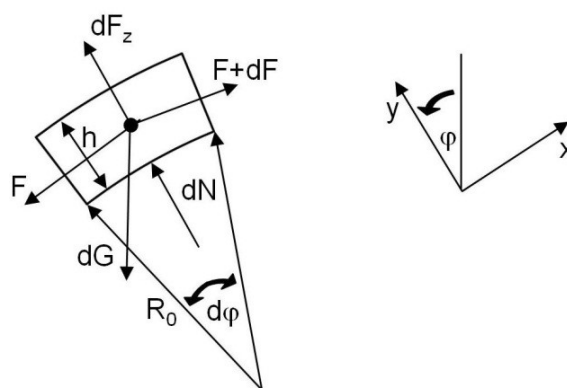
Figure 2 Forces on a rope element including mass and velocity

With the weight of a small element (Eq. 2) (A_B rope cross section and $R=R_0+h/2$)

$$dG = g \cdot dm = g \cdot \rho \cdot dV = g \cdot \rho \cdot A_B \cdot R \cdot d\varphi \tag{2}$$

and the centrifugal force (Eq. 3)

$$dF_z = \frac{v_0^2}{R} \cdot dm = \rho \cdot A_B \cdot v_0^2 \cdot d\varphi \tag{3}$$

the line contact pressure is calculated including mass and velocity of the rope (Eq. 4)

$$q = \frac{F - \rho \cdot A_B \cdot v_0^2}{R_0} \tag{4}$$

In the next step there is also friction F_R between rope and sheave considered (Fig. 3).
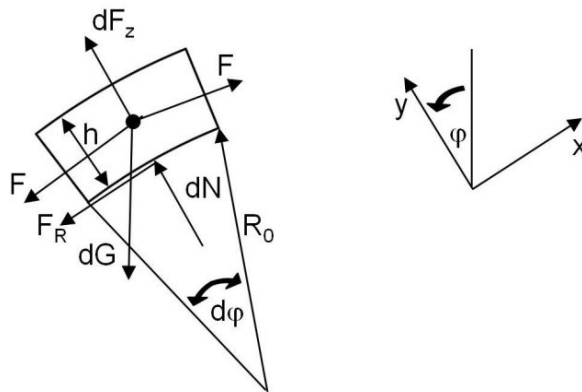
Figure 3 Forces on a rope element including mass, velocity and friction

The inequality of all forces provides the condition for adherence (Eq. 5) (μ coefficient of friction).

$$F \geq \frac{\rho \cdot A_B}{\mu} \cdot \left(g \cdot R \cdot (\sin\varphi - \mu \cdot \cos\varphi) + \mu \cdot v_0^2 \right) \tag{5}$$

With this equitation it is possible to calculate the limit between adherence and sliding of the rope (Eq. 6).

$$\varphi_{limit} = \arccos\left(\frac{\alpha \cdot \mu \pm \sqrt{\mu^2 + 1 - \alpha^2}}{\mu^2 + 1} \right) \tag{6}$$

with

$$\alpha = \frac{\mu}{g \cdot R} \left(\frac{F}{\rho \cdot A_B} - v_0^2 \right) \tag{7}$$

The existing calculation method of the line contact pressure between rope and sheave was extended with the mass and the velocity of the rope. So the line contact pressure depends now on the rope force, the bending radius, the mass of the rope and the velocity of the rope. Furthermore the new calculation method allows getting the limit angle between adherence and sliding of the rope with the sheave.

3   PRESSURE BETWEEN ROPE AND SHEAVE - MULTI-BODY-SIMULATION

Due to essential enormous processing power, it is currently not possible to simulate dynamically a completely detailed steal wire rope with all wires and strands by the finite-element-method, when the rope runs over the sheave. Therefore a practical numerical model based on a parameter assisted multi-body simulation model for the simulation of the dynamic run of a rope over a sheave was developed. This multi-body simulation model enables the calculation of contact forces between rope and sheave (Fig. 4).
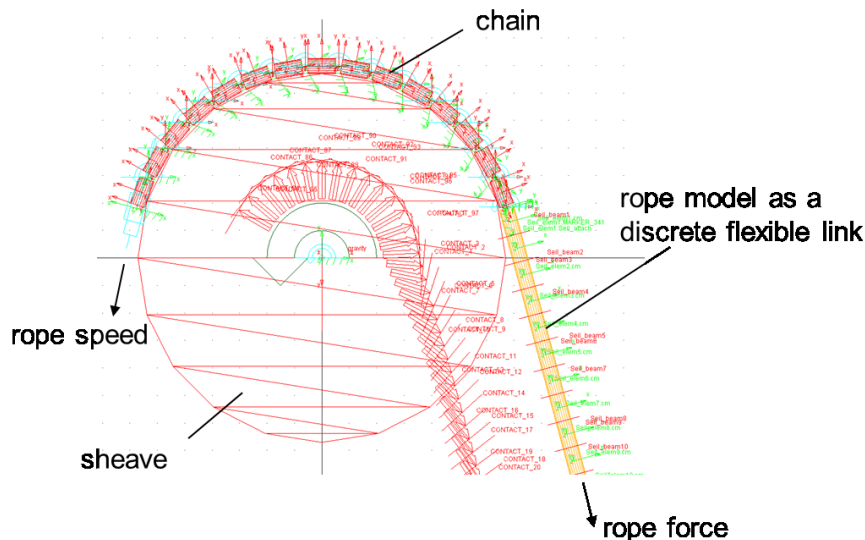
Figure 4 Multi-Body-Model of rope and sheave

Because of modelling the rope as a "discrete flexible link", the developed model of the rope enables simulation periods of few minutes. The discrete flexible link consists of fixed cylinder elements linked with beam-elements. The cylinder elements simulate both the external geometric form and the weight of the rope. The beam-elements represent the elastic part of the rope, which can be used for the assignment of Young´s modulus, bending resistance and damping coefficients of the rope.

In this model there is also a chain necessary, which consists of fixed cylinder elements linked with rotation joints. This chain moves the rope over the sheave. Because the starting position of the rope (the discrete flexible link) is only possible in a straight line.

Because it is an approximate model of the rope, it has to be calibrated with the help of results of experimental measurements. Therefore the results of measurement of the research study of Häberle [2] could be used and were prepared as the basics for the development of the multi-body-system. Furthermore the database was extended by own measurements on sheaves of a ship lift and a rope way used in practice. After the calibration of the analogous model, the model could be used for analyses which have not been possible so far. This resulted in the following findings.

3.1   Small wrap angles

By small wrap angles (smaller than 60°) the peaks of the line contact pressure go partially or completely together when the rope enters onto and runs off the sheave and this results in a noticeable higher contact force, which was unknown so far. With the developed numerical model for the first time it is possible to calculate these forces qualitatively and quantitatively. Within the analysed rope constructions there are maximum forces of 6 times of the constant (so far considered for the dimensioning of sheaves) part of the line contact pressure by small wrap angles (Fig. 5).

Therefore a calculation of the line contact pressure at small wrap angles by the given calculation method is no more acceptable.
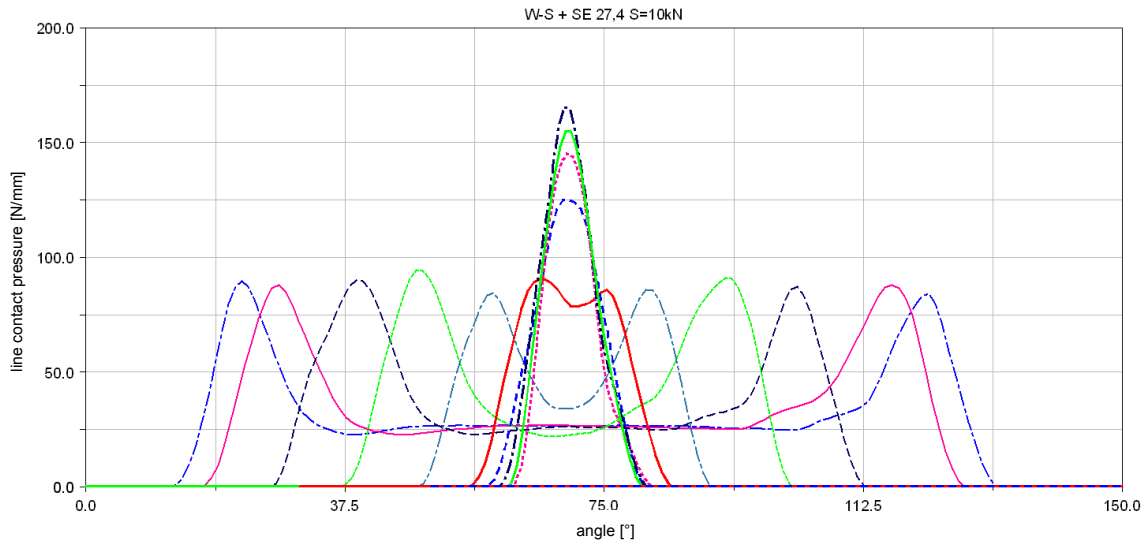
Figure 5 Influence of small wrap angles

3.2 Acceleration forces

At the start-up process or rundown of conveyor systems the rope force changes due to acceleration forces. This means that the contact forces between rope and sheave are variable and even higher during acceleration. For the first time these contact forces can be calculated by the help of the developed numerical model for a complete dynamic drive of the conveyor system with acceleration phase, phase with constant velocity and deceleration phase (Fig. 6). The rope forces (10, 30, 50, 70 and 100kN) are modelled as solid spheres with weight in this simulation to have the mass inertia represented. The results show that the forces between rope and sheave are directly proportional to the acceleration. Furthermore it is possible to analyse the effects of vibrations in longitudinal direction of the rope on the contact forces, because of the lurch at the acceleration. Furthermore this results in temporary higher contact forces.
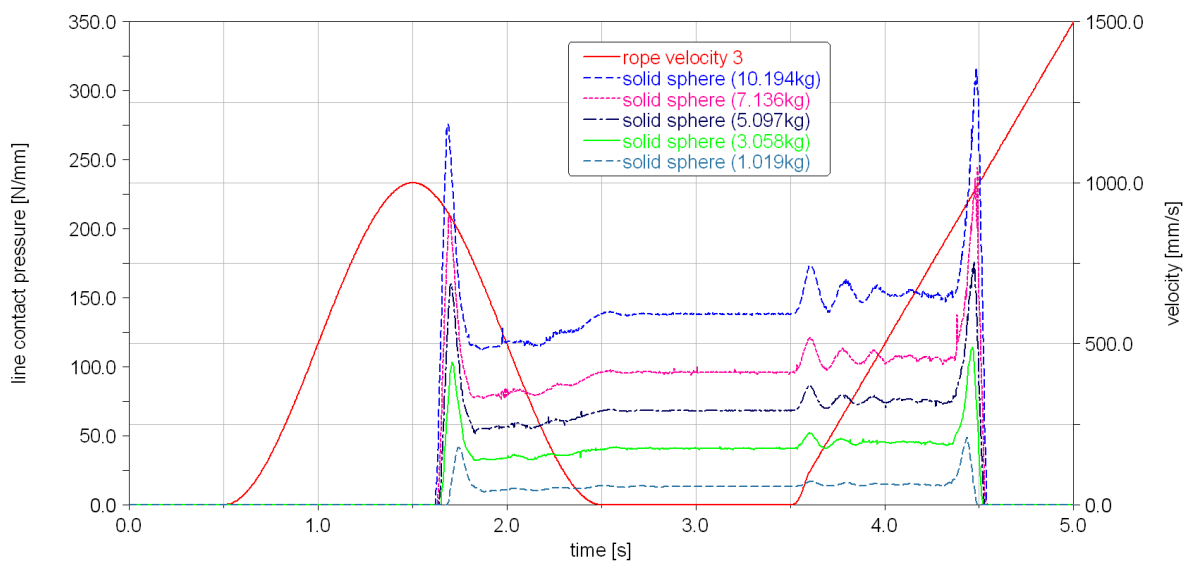
Figure 6 Influence of rope force during dynamic drive

3.3   Fleet angle

If there is a fleet angle between rope and sheave, which often cannot be avoided in wire rope drive systems, there are the same effects as if the rope entered onto or ran off the sheave. So because of the bending resistance of the rope, there are higher contact forces between rope and sheave, especially cross to the internal groove sidewall of the sheave. Up to now this could only be calculated with an extremely simplified analytic model. With the developed numerical model it is possible to calculate the amplitude and the course of the contact force for the first time (Fig. 7). The amplitude of the contact force is mainly influenced by the fleet angle and the rope force. Furthermore the geometry especially the angle of the internal groove sidewall has also an effect on the contact forces because of the fleet angle.
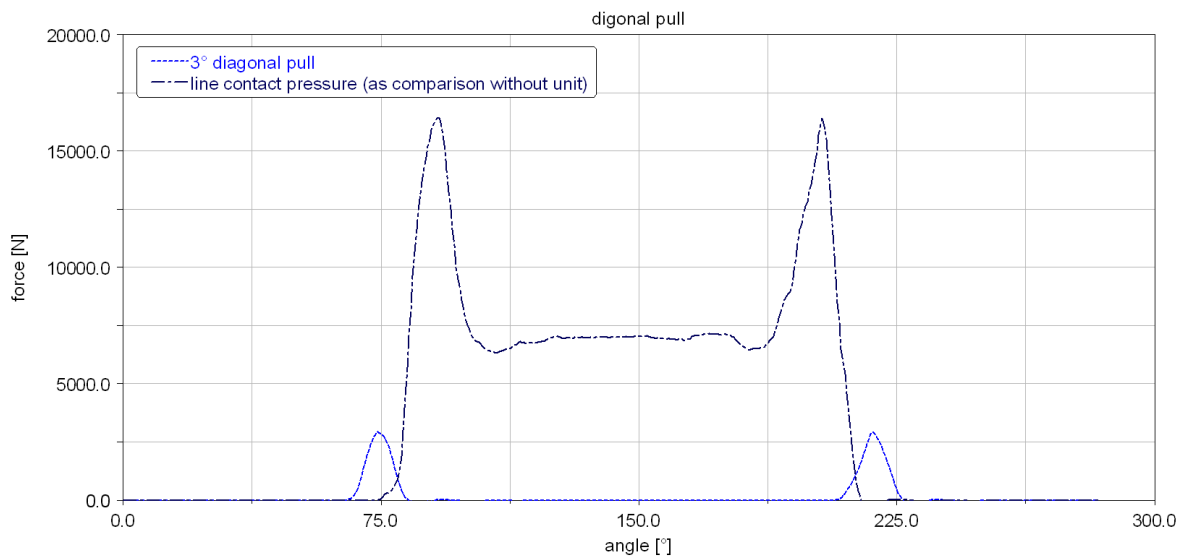
Figure 7 Influence of fleet angle

4   STRESS DISTRIBUTION OF BIG ROPE SHEAVES

Finally, in the research study a method for the calculation of the load of sheaves was developed, based on the finite-element-method for the calculation of the deformations and stresses of the sheave.

At sheaves with a spoke design or a similar spoke design, the critical position of the sheave is in general on the spokes (Fig. 8). These parts are alternately stressed with a combination of nominal tensile / compression stress and a superposed bending stress during rotation of the sheave. So the spokes are deformed in s-shape. The alternate bending stress of the spoke is relevant for the dynamic safety dimensioning of the sheave.
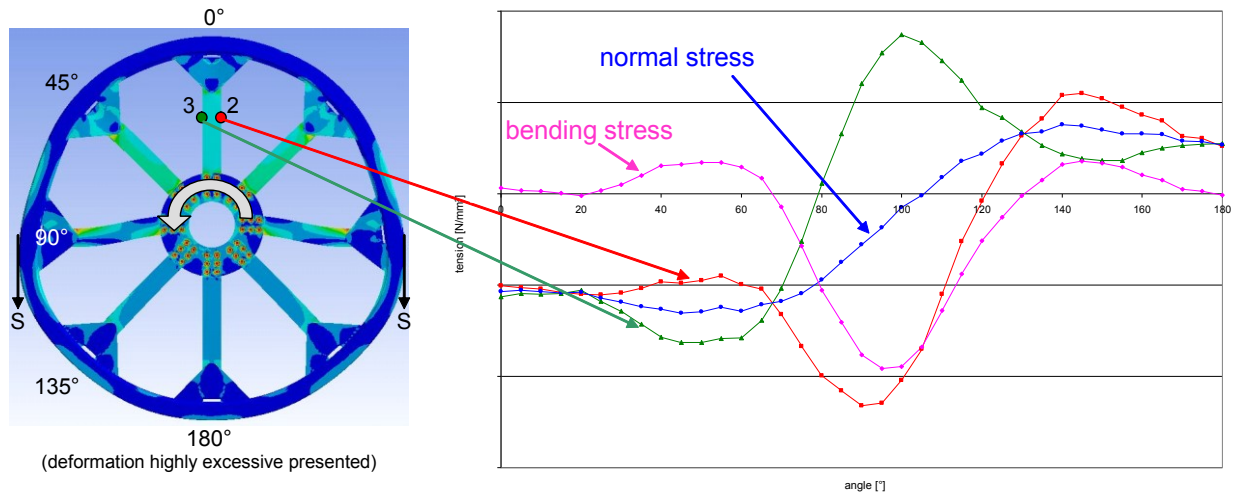
Figure 8 Stress distribution of loaded sheave

5   VERIFICATION

The verification of the developed calculation and simulation methods could be done by a sheave of a rope way used in practice (Fig. 9).

For the measurement of deformation of the sheave, strain gauges were positioned at the critical point (with the highest tension) on the sheave. All measurement equipment was located on the sheave, so that it was possible to measure the deformations during rotation of the sheave. The measurement included different load situations of the rope way system and also emergency stops.

Figure 9 Sheave of a rope way

These experimental measurements of this rope way sheave were successfully compared with the calculated results for that sheave (Fig. 10).
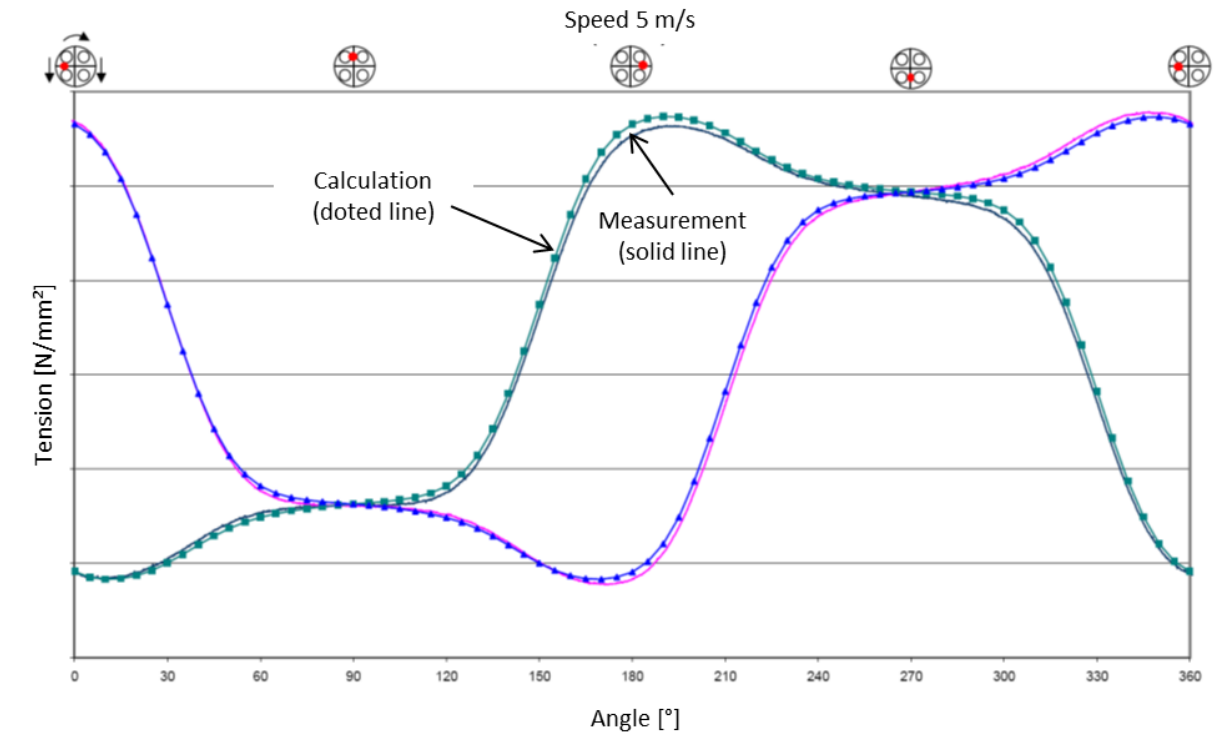
Figure 10 Comparison between calculation and measurement

6   SUMMARY

Within this research study the pressure between rope and sheave was analysed related to small wrap angles, dynamic forces and fleet angles. Therefore both an analytical model and a multi-body-model were generated to calculate these forces. With these results it was possible to calculate the stress distribution of sheaves with the help of finite-element-analyses. The experimental verification of the models has successfully been completed using a practical sheave – rope installation.

With this research study [4] an input for the systematically and safety dimensioning of big sheaves was contributed.

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Topic: *Calculation of the stress situation of big rope sheaves*

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The Effect of Randomization on Constraint Based Estimation of Elevator Trip Origin-Destination Matrices

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Abstract. We present a constraint programming formulation for the elevator trip origin-destination matrix estimation problem, and study different deterministic and randomized algorithms to solve the problem. An elevator trip consists of successive stops in one direction of travel with passengers inside the elevator. It can be defined as a directed network, where the nodes correspond to the stops on the trip, and the arcs to the possible origins and destinations of the passengers. The goal is to estimate the count of passengers for the origin-destination pairs of every elevator trip occurring in a building. These counts can be used to make passenger traffic forecasts which, in turn, can be used in elevator dispatching to reduce uncertainties related to future passengers. The results show that randomized search improves the quality of estimation results. In addition, the proposed approach satisfies real time elevator group control requirements for estimating elevator trip origin-destination matrices.

INTRODUCTION

Modern group controls typically plan elevator routes based on existing calls [1,2]. At any given moment, however, a passenger may arrive to an elevator lobby and give a new call which requires the changing of previously defined routes, if they are no longer optimal. By making forecasts of future passengers, the group control can avoid such unexpected route changes and improve passenger service level [3]. The forecasts should be based on complete information about the passenger traffic, i.e., on passenger journeys. A passenger journey is the journey of one passenger from an origin floor to a destination floor. The problem is that, especially during heavy traffic, the passenger journeys cannot be uniquely determined. They can, however, be estimated by solving the elevator trip origin-destination matrix (ETODM) estimation problem [4].

An elevator trip to up or down direction starts when passengers board an empty elevator and ends to a stop where the elevator becomes empty again. The passengers who board the elevator register calls that define their destinations, and the OD pairs of the trip. The boarding and alighting passenger counts can be obtained, e.g., by measuring stepwise changes in the load of an electronic load weighing device [5]. An estimated ETODM contains the OD passenger counts, i.e., the passenger journeys, for the OD pairs of the trip. The ETODMs estimated for a given time interval are added up to construct a building OD matrix (BODM) that describes the passenger traffic between every pair of floors in the building during that interval. The length of the time interval depends largely on the traffic intensity, but a typical interval is at least five and at most 15 minutes [6]. To learn the passenger traffic in the building, the BODMs of the same time of day or time interval, and usually day of week, are combined using, e.g., exponential smoothing [5]. The learned BODMs can be used to make forecasts about future passengers, namely, when and at which floors new passengers will register new calls, what is the number of passengers waiting behind the new and existing calls, and what are their destinations.

An elevator trip is analogous to a single transit route, e.g., a bus line, where there is only one route connecting any OD pair, and usually counts of the boarding and alighting passengers are collected on all stops on the route [7]. There are many methods for estimating the OD matrix for a single transit route. If the observed passenger counts are consistent, then a typical objective is to minimize a distance measure between the predicted and a target OD matrix subject to the so called

flow conservation constraints. They simply require that passengers travelling on the route do not disappear or multiply. The target OD matrix is usually based on historical data or a survey. A popular distance measure is the information minimizing function [8]. Similar estimators are obtained with the iterative proportional fitting method [7,9,10,11], and recursive methods [12,13,14]. Other types of estimators are obtained with constrained generalized least squares (CGLS) and constrained maximum likelihood approaches [11]. If the observed boarding and alighting passenger counts are not consistent, then a distance measure between the predicted and observed counts should also be minimized. Popular approaches are the maximum likelihood, the Bayesian and the CGLS method [15,16,17,18,19].

A single transit route is usually defined in advance and remains as such for long periods of time. This means that it is possible to collect many counts on the same route during a given time period, e.g., a rush hour, and use these counts to estimate average passenger counts for the OD pairs of the route. An elevator trip is request driven which means that there may not be two similar elevator trips even within a day. In addition, every elevator trip has its own set of OD pairs, and boarding and alighting counts. This is why we need to estimate a separate OD matrix for each elevator trip. Because there cannot be partial passengers, only integer solutions are acceptable. If the requests and the measured counts affect the domain of the predicted OD passenger counts then, unlike in a single transit route, they must be taken into account when defining whether an ETODM estimation problem is consistent or not.

In [4], the ETODM estimation problem was formulated as a box-constrained integer least squares (BILS) problem and algorithms for finding all solutions to the problem were presented. When all solutions are available and one is selected every time, e.g., randomly or as the average of the solutions, the BODMs are not affected by the algorithm used in solving the problem. In the long term, this strategy results in BODMs that model better the possible realizations of the passenger traffic, and enable robust passenger traffic forecasting in elevator dispatching. In [20], an ETODM was estimated by solving a succession of positive inverse problems. Both of the above methods can solve inconsistent problems, but the latter finds only a single solution to the problem. This is a not a good property when the goal is to construct BODMs for passenger traffic forecasting. In [21], the ETODM estimation problem was formulated as a linear programming (LP) problem. The presented approach, however, can be used only for consistent problems.

For implementing an ETODM estimation algorithm in a real elevator group control application, the algorithm must be fast to reduce CPU load, and to have the most recent information about the passenger traffic all the time. The BILS approach is faster than the LP approach [4,21]. However, since the ETODM estimation problem is in general NP-hard, all solutions to sufficiently complex problems cannot be found within a reasonable time which in a real application can be defined to be at most 0.5 seconds.

We formulate the ETODM estimation problem as a constraint optimization problem (COP) [22]. The formulation is based on elevator movements, e.g., stops, service requests, e.g., landing and car calls, and counts of boarding and alighting passengers. In addition to respecting a set of constraints, a solution to the problem is optimal with respect to a predefined distance measure between the predicted and observed passenger counts. We selected the least squares (LS) objective function because it favors solutions where the difference between all of the predicted and observed counts is small, which is reasonable considering a real application.

One advantage of the CP approach compared to the previous approaches is that both deterministic and randomized optimization procedures, resulting in a single or multiple optimal solutions, can be easily implemented. Intuitively, if only some (instead of all) of the optimal solutions can be computed within a real time limit, then a randomized search should result in BODMs that describe better the possible realizations of the passenger traffic, i.e., BODMs of better quality. The reason is that a deterministic search will always favor particular solutions. By using different deterministic and randomized candidate algorithms (CA), we study the effect of randomization on BODM quality. BODM quality is measured based on the total squared deviation

between the estimated and the true BODM. In addition, we compare the different CAs with respect to solving time.

CONSTRAINT PROGRAMMING FORMULATION

We define an elevator trip as a directed network of nodes $N = \{1, 2, \ldots, n\}$, and arcs A defined by OD pairs (i, j), $i, j \in N$. The node i corresponds to the ith stop on the elevator trip. Let r_i be the node at which a delivery request to the node $i \in N$, $r_i < i$, is registered. If no delivery requests are registered to node i, then $r_i = n + 1$. Let b_i and a_i denote the measured count of passengers who board and alight at node $i \in N$, respectively. The elevator capacity, expressed as number of passengers, is denoted with C.

We assume that:

1. At any time, there are less than C passengers in the elevator.
2. At least one passenger boards at node $r_i \neq n + 1$ and alights at node i.
3. Passengers do not alight at a node without a delivery request.
4. A passenger who boards at node $i < r_j$, i.e., before the delivery request to node j is registered, does not alight at node j.

The assumptions 2 and 3 imply that we trust the delivery requests. The fourth assumption means that the possible destinations of a passenger are defined by the delivery requests that are registered before or at the node where the passenger boards the elevator, which is usually the case in practice. This eliminates some OD pairs, and thus, an elevator trip often includes a smaller number of OD pairs than a single transit route where typically any node i forms an OD pair with any other node j, $i < j$.

The set of arcs A is defined as:

$$A = \left\{ (i, j) \in N^2 \mid i < j \ \wedge \ i \geq r_j \right\}. \tag{1}$$

Let $B_i \in [0, C]$ and $A_i \in [0, C]$ denote the predicted count of passengers who board and alight the elevator at node $i \in N$, respectively. Let $P_i \in [1, C]$, $i = 1, \ldots, n - 1$, denote the number of passengers in the elevator between the nodes i and $i + 1$. Finally, let $X_{ij} \in [0, C]$ denote the predicted passenger count along the arc or OD pair $(i, j) \in A$, i.e., the passenger count from origin i to destination j, that we want to estimate.

The predicted boarding and alighting counts must be consistent:

$$\sum_{i \in N} B_i = \sum_{j \in N} A_j. \tag{2}$$

Three formal rules for separating successive elevator trips from each other were presented in [4]. In general, an elevator trip starts at a stop where passengers board an empty elevator and ends to a stop where the elevator becomes empty again. Hence, at the first node, the predicted boarding count must be at least one and the alighting count zero, and at the last node the reverse must hold:

$$A_1 = 0, \ B_1 \geq 1, \ A_n \geq 1, \ B_n = 0. \tag{3}$$

At every node between the first and the last node, at least one passenger either boards or alights:

$$A_i + B_i \geq 1, \qquad 1 < i < n. \tag{4}$$

By taking into account the assumptions 2 and 3, the constraint in Eq. 4 can be more accurately stated as follows. According to assumption 2, at least one passenger boards at node $r_i \neq n + 1$ and alights at node i:

$$r_i \neq n + 1 \Leftrightarrow X_{r_i,i} \geq 1, \qquad 1 < i \leq n, \tag{5}$$

and according to assumption 3, passengers cannot alight at a node to which there is no delivery request, and thus, at least one passenger must board:

$$r_i = n + 1 \Leftrightarrow A_i = 0 \land B_i \geq 1, \qquad 1 < i < n. \tag{6}$$

This condition corresponds to the assumption that the elevator does not stop for nothing. In other words, if the elevator does not stop to serve a delivery request, it must stop to serve a pickup request which corresponds to at least one passenger.

The predicted OD passenger counts are related to the predicted boarding and alighting counts through the flow conservation constraints:

$$\sum_{j|(i,j)\in A} X_{ij} = B_i, \qquad \forall i \in N,$$
$$\sum_{i|(i,j)\in A} X_{ij} = A_j, \qquad \forall j \in N. \tag{7}$$

The number of passengers in the elevator between the nodes i and $i + 1$, P_i, is computed as follows:

$$P_1 = B_1, \qquad P_{n-1} = A_n, \qquad P_i = P_{i-1} + B_i - A_i, \qquad 1 < i < n - 1. \tag{8}$$

The elevator capacity is always respected because of the domain of the variables.

The problem of finding the passenger counts for the arcs or OD pairs of an elevator trip such that the predicted boarding and alighting counts are as close as possible to the measured counts can be seen as a network flow problem. In such a problem, the objective function is typically linear. A linear objective function may, however, result in a solution that produces small deviations between most of the predicted and observed counts, but accepts large deviations for some counts. This is not good since the difference between each observed and predicted count should be small. Hence, we consider the LS deviation between the predicted and observed counts as the objective function:

$$\sum_{i\in N} [(A_i - a_i)^2 + (B_i - b_i)^2]. \tag{9}$$

An optimal solution to an ETODM estimation problem is a vector of OD passenger counts X_{ij}, $(i,j) \in A$, that minimizes Eq. (9) with respect to the constraints in Eq. 2-8.

Note that the LS objective value in Eq. 9 is zero only if the problem is consistent. This is the case if:

$$\sum_{i\in N} b_i = \sum_{j\in N} a_j, \tag{10}$$

$$b_i \geq |OD_{ij}|, \qquad \forall i \in N, \tag{11}$$

$$a_j \leq \sum_{i|1\leq i<j} (b_i - |OD_{ik}|), \qquad \forall j \in N, \tag{12}$$

where $OD_{ij} = \{(i,j) \in N^2 | r_j = i\}$ is the set of OD pairs whose origin node is i, destination node is j and the delivery request to node j is registered at node i. Hence, $|OD_{ij}|$ is the minimum number of passengers that must be assigned from node i to nodes j. If the condition Eq. 11 does not hold, then the assumption 2 is violated. The set $OD_{ik} = \{(i,k) \in N^2 | r_k = i, k \neq j\}$ is the set of OD pairs whose origin node is i, destination node is $k \neq j$ and the delivery request to node k is registered at node i. Hence, the condition in Eq. 12 checks that the total count of passengers that can be assigned to OD pairs ending to node j is equal to or greater than the count of passengers who alight at node j, taking into account the minimum count of passengers that must be assigned to all other destination nodes k of origin nodes i.

Similar consistency conditions were defined in [4] but the corresponding BILS formulation is based on different assumptions. It first uses the observed boarding and alighting counts to divide the nodes to pickup and delivery nodes, and then the delivery requests to define the OD pairs. A node is defined as a pickup node if $b_i \geq 1$, and as a delivery node if $a_i \geq 1$. The disadvantage here is that if, e.g., the observed boarding count is zero even if the true count is positive, then the corresponding node will not be classified as a pickup node. If, in addition, the observed alighting count is zero, then the corresponding stop will not be included in the formulation at all. In both cases, the number of OD pairs will be smaller than it in reality should.

Our formulation is based only on the stops and delivery requests, which means that all stops will always be included in the formulation. Furthermore, according to Eq. 1, node i between the first and the last node defines always an OD pair with all nodes j such that $r_j < i$. This typically increases the number of OD pairs compared to the BILS formulation, which makes our approach more conservative. The two approaches will yield the same set of optimal solutions, if the formulations contain the same set of nodes, and they are consistent. A possible future improvement to the current formulation would be to consider also the variations in elevator load. More specifically, if at any stop i the arrival load is larger (resp. smaller) than the departure load, then $A_i > 0$ (resp. $B_i > 0$) while a constant load during the entire stop suggests that no alighting (resp. boarding) occurred. This would incorporate confidence of the measurements and help to correct unexpected human behavior. Note, however, that even if the arrival load was larger (resp. smaller) than the departure load, it is still possible that B_i (resp. A_i) should be greater than zero. This is because people have different weights. Hence, the load information can be used as an additional source of information but there should be another method to count the boarding and alighting passengers. A further research subject is to study which one of the alternative approaches gives better estimation results. In this paper, we concentrate on studying the effect of randomization and fulfilling real time elevator group control requirements with the proposed approach.

In destination control, passengers use numeric keypads to register destination calls at the elevator lobbies. Each destination call combines a pickup and a delivery request, and if every passenger would always register a destination call, then the OD passenger counts, i.e., ETODMs, would trivially be defined by the number of destination calls. However, it has been observed that people move often in batches and typically only one passenger of the batch registers the call to the destination [23]. It has also been observed that sometimes people abuse the destination control by giving several destination calls. Hence, the destination calls are not in general a reliable way to estimate the ETODMs. They could, however, also be used as an additional source of information.

To illustrate our formulation, consider the following instance: $n = 4$, $C = 20$, $b_1 = 10$, $b_2 = 1$, $b_3 = b_4 = 0$, $a_1 = a_2 = 0$, $a_3 = a_4 = 6$, and $r_1 = r_2 = 5$, $r_3 = r_4 = 1$. Since the condition (10) does not hold, the problem is inconsistent. Fig. 1 shows the corresponding ETODM estimation problem with the predicted OD passenger counts X_{ij}, $i,j \in A$, and the predicted boarding and alighting counts, $B_i, A_i \in [0, C]$, $i = 1,2,3,4$.
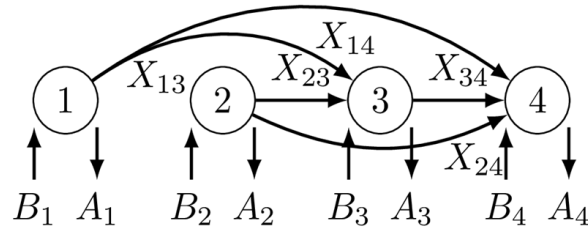
Figure 1 Example ETODM estimation problem

SEARCH ALGORITHMS

We consider a complete standard backtracking search which consists of a depth-first traversal of the search tree. At a node of the search tree, an uninstantiated variable is selected and the node is extended so that the resulting new branches out of the node represent alternative choices that may have to be examined in order to find a solution. The branching strategy determines the next variable to be instantiated, and the order in which the values from its domain are selected.

Branching Strategy and Candidate Algorithms. A branching strategy determines the next variable to be instantiated (variable selection), and the next value the variable is assigned from its current domain (value selection). The branching strategy strongly impacts the performance of the search by improving the detection of solutions (or failures for unsatisfiable problems) when building the search tree.

Here we consider the following variable selection strategies: *dom* (D) selects the variable whose domain is minimal; *dom/wdeg* (W) selects the variable that minimizes the quotient of its domain size over its weighted degree; *lex* (L) selects a variable according to lexicographic ordering; *random* (R) selects a variable randomly [24]. We consider only two classical value selection strategies: *minVal* (M) selects the smallest value and *randVal* (R) selects a value randomly. There is also a third classical value selection strategy, *maxVal*, which selects the largest value. However, our numerical experiments indicated that it is less efficient than *minVal*, and thus, is not considered in this study. A candidate algorithm (CA) is obtained by combining a variable and a value selection strategy. For example, DM uses *dom* for variable selection and *minVal* for value selection.

Optimization Procedure. Most CP tools use by default a standard *top-down* branch-and-bound algorithm which maintains a lower bound, lb, and an upper bound, ub, on the objective value. When $ub \leq lb$, the sub tree can be pruned because it cannot contain a better solution. Here, the problem is solved using the *bottom-up* procedure. The procedure starts with a lower bound, lb, as a target upper bound which is incremented by one unit until the problem becomes feasible. The first solution found by the *bottom-up* procedure is proven optimal. If (by luck) the first solution found by the *top-down* procedure is optimal, the optimality has to be still proven.

Let opt denote the optimal objective value. The *bottom-up* procedure solves $opt - lb$ unsatisfiable problems and only one satisfiable problem before finding an optimal solution. Hence, the number of problems that has to be solved is linear with respect to lb. Most *bottom-up* variants reduce from a linear to a logarithmic number of iterations in the worst-case. The *top-down* procedure is a good candidate if $opt - lb$ is large or the goal is to find good soutions quickly. In our case, the boarding and alighting counts are often measured without errors, and if an error is made, it rarely exceeds one unit. This means that the optimal objective value is often equal or close to zero, and thus, the *bottom-up* procedure with the initial lower bound equal to zero, $lb = 0$, is a good candidate.

NUMERICAL EXPERIMENTS

Simulation Process. We simulated lunch hour traffic in a 25-storey office building using the Building Traffic Simulator (BTS) [25]. The simulation time was 15 minutes. In a typical lunch hour traffic pattern, which was used also in this study, the proportion of incoming, outgoing and inter-floor traffic is 40%, 40% and 20%, respectively. We used a conventional group of eight elevators

with the capacity of 21 passengers, and adjusted the traffic intensity so that the handling capacity (HC) of the elevator group was insufficient. When the HC is insufficient, the elevators become often fully loaded, and thus, make many stops during one up or down trip. This increases the number of difficult problem instances. Because, in practice, elevator groups are designed to have enough HC, the problems occurring in reality are likely to be less complex.

Every simulation produces data, e.g., all passengers and their origin and destination floors that are used to construct the true BODM. An element in the true BODM corresponds to the true number of passengers from an origin to a destination. The simulation data are also used to construct the ETODM estimation problem instances. By solving all the ETODM estimation problem instances, and adding up the estimation results, we obtain the estimated BODM.

To obtain several sets of test data, we repeated the simulation 10 times with different seeds. The resulting 10 sets of problem instances contain only consistent instances. To obtain also inconsistent instances, we assumed a measuring accuracy of 90% and created inconsistent problem instances from the consistent problem instances by removing one passenger from each boarding and alighting count with 10% probability. Passengers were removed and not added since experience has shown that, at least with an electronic load weighing device, the observed count is typically one passenger less than the true count, if an error occurs. This resulted in 10 new sets of problem instances containing in total 165 inconsistent instances, which is about 30% of the total of 558 instances in the 10 new sets. This shows that since an elevator trip consists of several stops, the measuring accuracy per stop must be high in order to increase the number of consistent instances which are easier and faster to solve. Although the 10 new sets contain also consistent instances, we call them inconsistent to separate them from the sets containing only consistent instances.

BODM Construction. The BODM of a given time interval or simulation is constructed by adding up the ETODMs estimated during that interval. An ETODM estimation problem may, however, have several optimal solutions. We consider the first 10^K, $K = 0,1,2,3,*$, optimal solutions per instance and select the final solution as the average of the computed solutions. The $*$ sign refers to all optimal solutions. Because of the different branching heuristics, the different CAs will not give the same set of first 10^K optimal solutions, and thus, the final solutions will be different. This means that the BODMs estimated with different CAs will be different except for $K = *$. When we select the final solution to a problem instance as the average of the computed optimal solutions to the instance, we obtain always only one BODM per simulation.

Another reason for selecting the average is that, if only some of the optimal solutions are available, it describes the differences between the CAs with respect to the characteristics of these solutions. Hence, the average makes it possible to compare the CAs with respect to BODM quality. Note that the average of the computed optimal solutions is not in general the same as the continuous solution to the instance.

BODM Quality. The quality of an estimated BODM is evaluated based on the total squared deviation. Let X_{ij}^{true} and X_{ij}^{est} denote the true and the estimated passenger count from origin i to destination j in the true and the estimated BODM, respectively, and let N denote the total number of OD pairs in the building. The total squared deviation is the sum of the OD passenger count deviations between the estimated and the true BODM:

$$\sum_{i \in N} \sum_{j \in N} \left(X_{ij}^{est} - X_{ij}^{true} \right)^2.$$

(13)

Hence, the total squared deviation measures the proximity of the estimated BODM to the true BODM with respect to the OD passenger counts.

EXPERIMENTAL RESULTS

All the experiments were conducted on a Linux machine with 32 GB of RAM and a Intel Core i7 processor (6 cores -- 3.20GHz). The implementation is based on *choco* (http://choco.mines-

nantes.fr). We consider the deterministic algorithms DM, WM and LM. From the randomized algorithms, we consider only DR and RR for the reasons explained in the following sections.

A randomized search typically gives a different set of optimal solutions per problem instance when it is solved several times. Hence, to study the average performance of the randomized algorithms, we ran DR 50 times for consistent and inconsistent instances, and RR 50 times for consistent instances, but only 5 times for inconsistent instances because of much longer solving times. One run consists of solving all the 558 instances corresponding to the 10 BODMs once, and thus, each run produces 10 estimated BODMs.

Number of Optimal Solutions. Table 1 shows the distribution of the number of optimal solutions among the 558 consistent and inconsistent problem instances. It suggests that the search space is typically larger for the inconsistent instances. Table 2 gives the distribution of the LS objective value at the optimal solutions to the inconsistent problem instances. The distribution shows that the optimum of an inconsistent instance rarely exceeds one, which confirms that the *bottom-up* procedure with the initial lower bound equal to zero, $lb = 0$, is a good choice for optimization.

Table 1 Distribution of the number of optimal solutions

No. sols.	$= 1$	≤ 1	$\leq 10^2$	$\leq 10^3$	$\leq 10^4$	$> 10^4$
Consistent	405	84	35	19	13	2
Inconsistent	320	107	75	27	17	12

Table 2 Distribution of the LS objective value

Objective value	0	1	2	3
Count	393	136	27	2

Solving Time. Let t denote the solving time of a given problem instance for a given value of K, and let t_0 be the minimum solving time among the CAs for the instance and the value of K. Table 3 shows the geometric mean, geometric standard deviation and the maximum of t/t_0 computed over all inconsistent instances and values of K. The geometric mean and standard deviation are used since the arithmetic counterparts are not suitable for normalized values [26]. These results are not shown for consistent instances since the differences between the CAs were negligible. It can be concluded that DM is usually faster and more stable than WM and LM. Hence, *dom* is the best deterministic variable selection strategy with respect to solving time.

Table 3 Performance of the deterministic CAs with respect to solving time

	DM	WM	LM
Geom. mean	1.005	1.036	1.044
Geom. std	1.039	1.050	1.154
Max	2.562	3.710	11.684

Fig. 2 shows the percentage of inconsistent instances solved within a given time for four selected CAs, namely, DM0, DR1, RR2 and DM∗. The last character corresponds to a given value of K. For example, the graph of DM0 shows that DM can find the first solution to more than 95% of the inconsistent instances in less than 0.2 seconds. Although not shown, all other similar graphs for the deterministic CAs stay within the graphs of DM0 and DM∗. As shown in the upper right corner of the figure, RR1 takes more time for some instances than DM∗, which means that randomized variable and value selection is not a good strategy since we can find all solutions with a deterministic algorithm faster. There are, however, a few problem instances to which it takes clearly a longer time to find all solutions as shown by the graph of DM∗. DR2 produces an acceptable increase in solving time, but although not shown in the figure, the solving times of DR3 become too

long. It can be concluded that DR should be preferred over DM for $K = 0,1,2$, if it increases BODM quality.
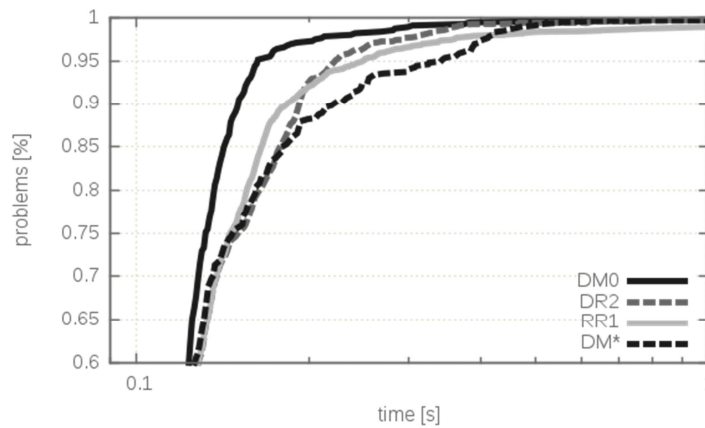
Figure 2 Cumulative distribution of solving time for four selected CAs

In [4], the solving time of the BILS algorithm in finding all optimal solutions to four consistent and inconsistent example problem instances is reported. Table 4 shows these results also for DM which is a little bit slower except for the inconsistent instances 3 and 4 for which DM is much faster. In general, the solving time of DM is acceptable considering a real application although for the inconsistent instance 3, the 0.5 seconds limit is somewhat exceeded. The example instances were formulated using the BILS formulation. With the CP formulation, the number of optimal solutions to the inconsistent instances 2, 3, and 4 are 44, 14091 and 155, respectively. This illustrates the differences between the two formulations.

Table 4 Comparison of DM and BILS

	Consistent				Inconsistent			
Instance	1	2	3	4	1	2	3	4
DM solving time [s]	0.13	0.14	0.27	0.2	0.14	0.18	0.66	0.26
BILS solving time [s]	0.00	0.00	0.13	0.08	0.00	0.00	2.24	117.5
No. sols.	1	5	2016	9	5	29	10353	78

Total Squared Deviation. Fig. 3 shows the total squared deviation of the deterministic CAs for inconsistent instances as a histogram. The total squared deviation for each BODM is computed based on Eq. 13, and the results shown in the figure are obtained by summing up these deviations. The CAs are grouped by the parameter K, $K = 0,1,2,3$, and the horizontal line is the total squared deviation for all optimal solutions, which is the same for all CAs. The corresponding histogram for the consistent instances is not shown since it looks exactly the same except that the total squared deviations are smaller. The main result is that finding multiple optimal solutions reduces the deviation. In addition, DM and WM are almost equivalent and LM results always in the greatest deviation, which again makes DR a better choice than WR and LR.

Table 5 shows the average total squared deviation of DR and DM for the inconsistent instances. It can be concluded that DR is on average better than DM. However, if we consider the 0.5 seconds limit, then DM is a better choice since based on Fig. 2, DM∗ can solve approximately as many problem instances as DR2 within this limit and the BODM quality of DM3 is already better than that of DR2. For shorter time limits, DR is a better choice.

Number of Passengers. For inconsistent instances, the total number of passengers in the estimated BODM is typically less than in the true BODM. The reason for the underestimation is naturally that the inconsistent instances were created by removing passengers from the true counts. However, underestimation is an issue also in reality and, as shown in Table 6, the amount of underestimation depends on the CA. The amount of underestimation is obtained by subtracting the total number of passengers in the true BODM from the total number of passengers in the estimated

BODM for each of the 10 BODMs, and then adding up these differences. Note that also overestimation might be an issue in practice but, as with underestimation, this depends on the measuring accuracy and the used measuring device and method.
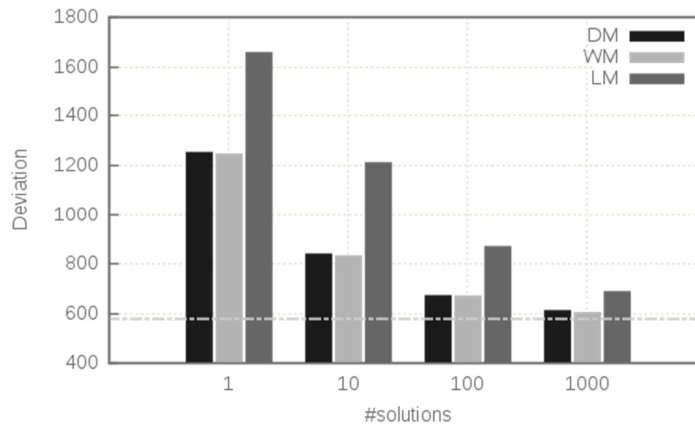
Figure 3 Total squared deviation of the deterministic CAs

Table 5 Total squared deviation of DR and DM

K	0	1	2	3
DR	1179.0	762.1	653.4	599.2
DM	1255.0	843.5	676.9	616.5

Table 6 shows that both randomized CAs significantly reduce the underestimation, especially when only one optimal solution per instance is computed. Even the worst cases (max) are better than the results obtained with DM. DR results on average in smaller underestimation than RR. Furthermore, the more optimal solutions are computed the more accurate and the more stable is the estimated BODM. These results support the selection of DR over DM.

Table 6 Underestimation of the number of passengers

	DM	DR				RR			
K		Avg	Std	Min	Max	Avg	Std	Min	Max
0	175.0	16.2	6.0	10.0	30.0	22.6	8.5	14.0	33.0
1	79.3	35.1	1.6	32.1	38.8	38.4	2.0	36.1	40.9
2	58.7	39.1	0.6	38.0	40.9	40.9	0.9	39.8	42.1
3	50.6	40.6	0.3	40.1	41.3	42.0	0.5	41.5	42.6

CONCLUSIONS

We presented a constraint programming (CP) formulation for the elevator trip origin-destination matrix (ETODM) estimation problem. An elevator trip consists of successive stops in one direction of travel with passengers inside the elevator, and the estimated OD matrix contains the OD passenger counts for the OD pairs of the trip. The ETODMs estimated for a given time interval are added up to construct the building OD matrix (BODM) of that interval. The passenger traffic in a building can be learned by combining the BODMS of the same day or time interval, and usually day of week. These matrices can be used to make forecasts about future passengers. The forecasts are needed in elevator dispatching to improve dispatching decisions with respect to future passengers.

An ETODM estimation problem may have many optimal solutions, and any of these solutions may correspond to what happened in reality. To obtain robust forecasts, the learned BODMs should describe the possible realizations of the passenger traffic as well as possible. This can be achieved by finding all or several optimal solutions to each problem instance and selecting the final solution, e.g., randomly or as the average of the optimal solutions.

We compared three deterministic and two randomized CP algorithms in finding a predefined number of optimal solutions to the ETODM estimation problem. Several test problems were obtained by simulations of lunch hour traffic in a typical multi-storey office building. The traffic intensity was adjusted above the handling capacity of the simulated elevator group. This resulted in complex problem instances that enable robust performance testing and comparison of the algorithms.

The comparison of the algorithms was based on solving time and BODM quality which affects the reliability of the passenger traffic forecasts. The results suggest that randomization and multiple optimal solutions is a good compromise between solving time and quality. For very complex problem instances, the fastest CP algorithm turned out to be even faster than the previous estimation approaches and algorithms. In addition, the proposed approach fulfils real time elevator group control requirements for solving ETODM estimation problems.

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The Development of a Low- to Mid- Rise Energy Efficient, Green Lift System

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Abstract. This paper explains and discusses the drivers, aims and the design process applied in a research and development project to develop a low- to mid- rise green lift system. The particular technologies that have been in this work include a new lift car design, adjustable counterweight system, lift control system, energy efficient drive system, lift monitoring system, belt suspension and improvements in lift installation technique.

1   INTRODUCTION

In the modern built environment there is a strong need and continued demand for the design of efficient and environmentally friendly ('green') vertical transportation systems. In this context, the green lift system design is undertaken within the framework of Knowledge Transfer Partnership scheme. The paper summarizes the research which has been carried out to develop a novel, efficient Machine Room-Less (MRL) low- to mid- rise lift system incorporating a number of modern technologies.

A new MRL system that addresses the inherent problems brought about by economics, current lift practices, environmental challenges and safety standards has been designed. The design of the system is optimized to achieve better efficiency. The lift installation process and the issue of reducing its energy consumption have been investigated in the paper.

2   GREEN LIFT

2.1   Energy efficiency

Although the topic of improving energy efficiency of a lift system was investigated recently on numerous occasions [1], the state of the industry in the UK, particularly in the low- to mid- rise applications, often concentrates on economics rather than constant improvement. This paper is aimed at changing this perception and proposes new solutions that might challenge the current state.

Many people in the industry, primarily lift engineers and lift operators, consider that lifts are already very efficient and account for 5% energy used in offices [2], and according to CIBSE guide F for between 5% and 15% of energy used in some buildings [3] (Other authors quote figures between 3-5% for lifts, escalators and moving walks combined [4] and between 3-8% for lifts according to Asvestopoulos and Spyropoulos [5]). This point of view is understandable for a practitioner, who concentrates on main principles such as economics, mechanical and electrical performance of the system. This is, however, not justified when taking a holistic approach to the energy usage and sustainability of a country. A study presented in the recent work [6] estimates energy saving potential in the European residential sector for 62% of current energy consumption when the best available technology is used. Thus, all efforts concentrated on promoting any incentives that might lead to change and improvement of the current state should be considered.

Energy performance of a lift system in Europe can be currently calculated and classified using the document developed by Association of German Engineers (VDI 4707). The new international

standard ISO 25745-2 is expected to be released in the near future and will become a new, widely accepted benchmark and a reference for all new installations. Both methods are similar in the approach to energy calculation and classification. The problem in all cases is that calculations are based on estimations of lift usage for a specific building. This might be sufficient for an initial evaluation, however the next step in evaluation of energy consumption in a lift system would be continuous monitoring, recording all values of lift travel, load in the car and electrical current drawn from the mains supply. An energy usage model which is informed by data from the continuous monitoring system would then allow for a much greater control of the system improving overall efficiency by suitable control strategy.

2.2   Lift System

New technology solutions that are implemented in the project include the following:

-    Lift car design and optimization of modular lift car design.

-    Adjustable counterweight technology.

-    New, software based control system.

-    Open protocol remote monitoring system (the i-COM) with modular capability, accessible from internet-enabled devices

-    The latest technology drive and suspension system.

-    Improvements in the installation technique.

2.3   Lift Car Design

A virtual model of a lift car was developed with the use of Computer Aided Design (CAD) software, which allowed for an accurate and detailed model before any manufacturing will take place. The lift car design is based on a lightweight aluminium framework. This solution benefits from versatile structural options, allowing for implementation of the lift car design in a broader range of sizes, depending on the requirements. Additionally this also allows for limiting the number of traditional fasteners used. Another factor that was taken into account in the design process was an improved installation methodology, where the components are pre-manufactured in the factory, being delivered to the site and installed with minimum work required, due to the secret fixings and modern adhesive bonding used in the process.

The design implements new, cost-efficient composite panels developed for the aerospace industry applications. The panels are of a special construction allowing for better noise and vibration characteristics and a shorter lead time. Another benefit of this solution is the number of parts required. As the panels are cut to size before assembly, it effectively limits the number of panels required per side and further limits the number of fasteners and fixings necessary. Most importantly, the characteristics of panels are such that these panels are of improved fire-resistance as well as of smoke and toxicity properties, allowing them to be used in the modern built environment. Additionally, bespoke design of the car allows for quicker and flexible response to the customer needs.

Benefits of this solution include: limiting the mass of car leads to limiting mass of other components (counterweight); limiting the number of components (panels) lead to reducing the time to manufacture, limiting the number of fasteners reduce mass of car, special fixing solution allow for shorter installation time, limiting the mass of components and simplification of assembly process would allow for reduced installation time. All this improvements will reduce carbon footprint of a lift car. This in effect is a reduction of energy used in manufacture and installation. Additionally reduction of masses will require less energy for acceleration.

2.4 Adjustable counterweight design

Advancement of technology, particularly drive inverters and regenerative systems allowed for improvement of energy efficiency of an MRL lift system, reclaiming energy used in the regenerative phases of a four quadrant operation. These systems provide the required functionality; however there are implications for the actual savings that might be achieved. The main problem of these systems is that regeneration will never be the perfect solution, as the mechanical energy is converted into electrical energy and back into mechanical energy. This is related to losses due to component efficiency which multiply themselves in the cycle. Additionally, from a mechanical point of view, the system is also less efficient when the car load is significantly different from the counterweight balance. So if it is balanced to 0.4-0.5 of the rated load, this leads to a situation that the energy is consumed even when the lift car is moving without load. Statistically this situation occurs in 50% cases of lift travel [6]. One more fact is that people transfer in the building is balanced – traffic in is equal to the traffic out. It is clear that there are exceptions to this, particularly when people use the stairs to go down more often that to go up.

All this has facilitated an improvement in the determination of an adjustable mechanical system that might feasibly be implemented in a low to mid rise lift system. Possible energy gains have been quantified based on the results of lift traffic surveys and correspondingly generated traffic patterns. A virtual model of the adjustable counterweight system has been developed, showing the operational principle and the mechanical components. This work can lead to a more efficient mechanical design of a lift system in certain circumstances. One limitation of this solution is that it can only be incorporated in low and mid-rise systems when the peak traffic is within its rated capability. The advantage of the proposed system is that it can potentially be used as an add-on without redesigning the existing MRL arrangement.

2.5 Control System

The energy performance of a lift system depends on the following two main operational components: running and standby energy consumption. Thus, it is important that the new lift design addresses the issue of energy consumption in both areas. Recent research suggested that the standby energy efficiency of a lift system can account for 5% to 95% of its energy consumption [4], depending on a particular system and its usage patterns and energy consumption during running condition and standby.

New, software based control system programmed in C using Microsoft technology would allow for substantial improvements in panel size as compared to a traditional panel with logic gates, reduction of control system components, time required for manufacture and improved efficiency of the system therefore reducing energy consumption. System software allows to operate the panel in "Eco mode", reducing the energy used for lights and fans during operation and to set the system to the 'Standby' mode. Two additional features that allows for improvement in energy efficiency of the control system is drive standby and micro-controller standby function which could be used during periods of inactivity. Size of all main components used in the panel design allows implementing the main panel in the landing door frame. This offers a significant advantage in the MRL lift arrangement as in this type of lift most problematic is the access to the control cabinet.

2.6 Monitoring System

The newly developed remote monitoring system (i-COM), allows for a continuous monitoring of a number of parameters in the lift. This in turn determines an efficient service schedule thus reducing the costs to the maintenance company and the customer. Parameters, which are directly related to the ride quality, are currently implemented in the monitoring system, including velocity, acceleration and jerk. Additionally it is possible to monitor other properties of the system such as drive parameters, fault log, waiting time statistics, floor levelling statistics, floor usage statistics, maintenance log and remote control of the lift.

A system based on CAN-bus technology would allow ultimately for a number of modules to be connected, namely:

1) Voice transmission module (autodialer)

2) Continuous load monitoring module

3) Condition monitoring module (state of machine, bearings, guide rail performance and lubrication). This solution would allow for a determination of component degradation and predictive maintenance ensuring energy efficiency and a minimum out of service time.

Remote monitoring system has also allowed for further improvements in standby energy consumption of a lift. Periods of inactivity can be logged in the control system, allowing to visualize and decide on particular control strategy, effectively allowing to switch off most of the components on a periodic basis. In case of seasonal operation, monitoring software can allow for further savings, such as reduction of lift speed.

2.7   Drive system

The system benefits from an underslung, 2:1 drive, using polyurethane multi-belts with steel sheaves and pulleys. Implementation of a belt system instead of traditional steel wire ropes has a number of advantages, such as reduced size of traction sheave which allows for a smaller machine running at higher speed, reduction of rope and sheave wear and improvements in ride quality. Other benefits include reduction in overhead clearance required for machine, reduction in space required for car pulleys, reduction in cost of replacement as the belts benefit from greater longevity. Problems in this type of project include design and selection of components, belt monitoring system and certification. A similar solution was used for years by major companies in the lift market, however because of patents on particular designs and solutions, this did not become an industry standard.

The lift is driven by brushless Permanent Magnet Synchroneous Motor (PMSM), a type of rare earth magnet induction motor which benefits from a higher power density for their size as compared to AC Induction motors (ACIM). Use of PMSM in the lift industry is increasing as it allows for more compact design and provides highest efficiency in comparison to ACIM [6].

2.8   Installation technique

The study conducted within this research project has led to consideration of improvements in the installation techniques for low- to mid- rise lift systems. Two particular areas are under investigation, which are using laser sensors to provide accurate alignment of drive and guiding and evaluation of solutions available to reduce installation costs. Laser solutions that were introduced to the lift industry in the past are increasingly used in a number of industries such as automotive, wind power, manufacturing, nuclear, aerospace, and marine [7]. Although the range of applications was investigated in the past it is considered that the area is not sufficiently exploited in practice.

3   CONCLUSION

Main restrains to the energy efficient development that were determined by De Almeida et al. [4] include lack of monitoring of energy consumption, awareness and knowledge about energy efficient technology. In this project it was considered to tackle all three main barriers, which would change the common perception of a lift system as optimally designed.

Other barriers that can be identified based on recent work are particular manufacturer restrictions on the technology (patents), lack of availability of components and UK market demands in the low- to mid- rise lift sector. In order to progress further and to satisfy the modern ecological demands

towards a more sustainable environment further research and development effort is needed to be implemented, particularly within the small and medium size enterprise in the lift engineering sector.

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BIOGRAPHICAL DETAILS

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Charles Salter is the owner and Managing Director of ACE Lifts. He has over 35 years of lift industry experience, 25 of those establishing and running ACE Lifts (formerly Artisan Control Equipment). His area of expertise is in the electronic aspect of lifts; specifically control systems and remote monitoring and has contributed to a number of industry texts regarding these. Charles is currently studying for an MSc in Lift Engineering at Northampton University.

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Environmental Impact of Lifts

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Abstract. Lifts are active products, that is, they consume resources to fulfil their function. For this reason, their environmental impact will last their whole lifetime. In this type of product, the usage phase has traditionally been assumed to be the most relevant one from an environmental point of view. Unlike other products fulfilling the same transport function, lifts are inherently linked to the medium in which they are installed. Thus, they are tailored design to fit the needs of the population of the building where they will be operating. The fact that lifts are multi-user products conditions their performance and makes it difficult to estimate their usage, but the ISO 25745-2 current draft (for public comment) [1] provides with a quite accurate simplified method based on figures obtained from thousands of simulations. If the boundaries of the analysis are extended to cover its complete useful life down to its disposal, the results show that the usage phase is not necessarily the most relevant in all usage categories. In this paper, an overview of the distribution of the environmental impact of lifts is presented. The results are analysed to determine what the key factors are. Finally, indications on how to interpret the environmental data provided by a lift supplier are given to allow architects and lift consultants the selection of the most environmental friendly lifts during the building design phase.

1   INTRODUCTION

1.1   What is life cycle assessment (LCA)?

A Life Cycle Assessment 'LCA' (also known as life cycle analysis, eco-balance or cradle-to-grave-analysis) [2] consists of the investigation and valuation of the environmental impacts of a given product system during its useful life. This assessment is based on the input-output analysis of physical flows (materials, energy, emissions, etc.) and their relationships at all stages of this life cycle, from the raw materials phase to the transport of the final product. Once delivered to the customer, Energy-using- (EUPs) or energy related products (ERPs) [3] will, because of their nature, cause further environmental burdens or will have an influence on the impact of other product systems until the end of their estimated life period. Finally, environmental flows will be interchanged with the environment during the product disposal, valorisation and/or recycling in the corresponding treatment facilities. This holistic assessment approach, which allows detecting whether a design change is actually shifting environmental burdens from one stage to the other within the product supply chain, makes Life Cycle Assessments (LCAs) the best tool for assessing the potential environmental impacts of products currently available.

The LCA methodology is described in the Standards ISO 14040 [4] and 14044 [5] and is complemented in technical reports [6,7] Additionally, ISO 14050 [8] defines most of the terminology used in the two previously mentioned standards. All leading companies in the transport sector, including all big lift manufacturers, are promoting sustainable production and consumption and use the LCA methodology to assess their products from an environmental point of view already in the development phase [10].

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1.2   Communication of environmental data

The above mentioned ISO standards are valid for the assessment of any product or service. For this reason, they just describe the "principles and framework" [4] and the "requirements and guidelines" [5] to apply the methodology and they leave many aspects undefined and therefore subject to the choice of the practitioners. This flexibility implies that the results of two Life cycle impact assessments (LCIAs) can only be compared if they are delivered with an extensive report detailing how the assessment has been conducted and if this report has been critically reviewed. Nevertheless, this is neither an efficient business to business, nor an effective business to customer communication way. Instead, companies utilise environmental declarations [11], which can be of three different types: Type I [12], Type II [13] and Type III [14]. Their degree of credibility and transparency varies because the procedures to issue the labels and the schemas ruling them, also standardized, are different. Whereas Type II is a self-declaration, type I and III are based on the life cycle approach and shall/can be verified by third parties. Type III declarations, in contrast to type I give quantitative information of the final (or intermediate) product based on a set of specific rules, requirements and guidelines called Product Category Rules (PCRs). They are mainly used for business to business communication and are for this reason primarily launched by industry initiative. The lift sector is currently undergoing the development of these rules [15].

2   DEFINITION OF THE OBJECTIVES AND METHODOLOGY

The lift sector is highly fragmented and its supply chain is long and complex. Some components and sub-components manufacturing processes, logistic and installation works can be carried out by a medium, small or micro company different than the one selling the lift. This aspect complicates the issue of conducting a complete life cycle assessment, increasing the duration and difficulty of the data collection process and the cost involved. Additionally, the fact that there are not two identical lift products in the market, except if they are installed in the same building, makes it necessary to assess each individual lift unit apart or to create a good database that can be used to extrapolate results.

2.1   Objectives

The purpose of this research was to define a method to conduct LCAs of lifts with the less possible effort, but providing the most possible reliable results, thus allowing their publication and their use for comparison of two competing lifts products over their entire life cycle. The development of the method involved a first screening study, in which the constituting parts of the product system, as well as the elementary flows that were important with view to the final results were identified. The screening highlighted the relevance of the usage phase and lead to further investigation, the results of which are contained in the ISO 25745-2 Standard [1]. After a sensitivity analysis, the study was later completed to fill in the data gaps existing. Further details like product structure to be used, background data for the assessment, information requirements regarding the product maintenance and replacement, rules for the assessment of the use phase, end of life treatments and responsibilities in the reporting can be found in [10].

The method suggested is valid for specific and model lifts and can be used both by complete lift supplier/manufacturers and by any other actor of the supply chain: component manufacturers, installers, maintainers etc. requested to supply information about their products or processes. It can be applied to assess new and existing products and all technologies, including less energy efficient ones, like for example hydraulics. These lifts may not beat the energy consumption values of electric lifts competing with them for the same application, but they might be more advantageous in other phases of their life cycle like product manufacturing, installation and maintenance (less demanding), or even at the end of their life because they may have a higher reuse or recyclability rate, as suggested in some studies from hydraulic lift manufacturers [20,21].

2.2   Methodology

The LCAs were conducted in the four steps suggested by the standards: Goal and scope definition, life Cycle Inventory analysis (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation. The definition of the goal of the study is the first and most important step, because it is aligned with the intended application of the results obtained and therefore conditions the methodology to be applied and the degree of depth and rigour requested. In this section, the definition of the goal and scope will be explained. Section 3 of this paper contains the results of the three remaining LCA phases.

2.2.1   Goal and scope definition

The methodology covered a "cradle to grave" analysis including all the life cycle phases directly related to the product until its disposal and end of life treatment. The reinstatement of reused components back in the in the same life cycle chain was excluded because of the lack of statistical data. The use of recycled material was accounted in the input materials from the databases only in those cases where the % of recycled material composition was known.

2.2.2   Functional unit

The main function of a lift is the vertical transportation of goods or passengers in buildings from floor to floor, therefore the best lift for a certain application will be the one able to transport the amount of passengers or loads in transit in the building during a certain period to their desired destination causing the least possible environmental burdens. Considering this, possible functional units are: Passenger.Floor, kg.Floor, Pkm (Passenger.km), kg.km.

2.2.3   Lift structure

For the inventory, the lift must be broken up into its major components. The information was obtained from the software application used by the lift company collaborating in the study to configure the product and from the ERP. These are in some cases linked.

The sum of the weights of the components inventoried matched with the theoretical weight of the lift. The lift structure reflected the actual supply chain, so that the responsibility regarding the provision of the inventory information was clear. In this way, double counting of parts can be avoided. In [10], a proposal for a standardized lift structure that incorporates all possible lift components according to their function and considers the economic flows in the sector is provided.

2.2.4   System limits

The system limits were established taking into account the influence that the lift suppliers have in the environmental impact caused by their products. This responsibility included the usage and maintenance phases, because the lift performance depends on the design and the quality standards adopted for their components. Processes like building a production site, infrastructure, production of manufacturing equipment and management personnel activities were left outside the boundaries because of the lack of data and because they are not expected to have a significant influence in the results used for comparison. Other data like the impact of manufacturing intermediate parts and subcomponents or their transport were also left aside because of the impossibility of collecting reliable information.

2.2.5   Processes of the Lift life cycle

The processes along the product supply chain can be classified as upstream, core or downstream processes [16] depending on the responsibility that the company conducting the assessment has on them. They can also be classified as foreground and background processes, depending on whether there is direct access to environmental information or not. Following, the processes and information on how they were considered in this study is given.

Upstream processes considered (The environmental background information was obtained from environmental databases of LCA software)**:**

-   Production of raw materials (extraction and refining)
-   Production of auxiliary materials (like those used for the manufacturing processes)
-   Production of semi manufactured goods (not considered)
-   Water supply
-   Production of heat and electricity
-   Transport

Core Processes: These are all relevant unit processes taking place within the organisation of the product subject of assessment.

-   Lift components material composition including packaging. Upstream data were used for the inventory.
-   Lift components manufacturing. Only the manufacturing processes of the first level suppliers, tier 1, were considered for the first study. Manufacturing processes of suppliers were excluded from the second study. The treatments of wastes generated within the process were considered too.
-   Production of parts and subcomponents. Data of components (like electric and electronic equipment) are available in databases. Foreground data were not collected.
-   Components assembly. This activity can be carried out at the components manufacturing site or during the lift installation. Its environmental impact is however negligible.
-   Lift components storage (intermediate storage of components). Only transport from first level supplier to lift manufacturer considered. Intermediate transports or storage time not considered.
-   Lift components distribution to the Building site[2], (upstream data used for transport activities).
-   Lift installation. Mainly impact of workers displacements. Its impact is however negligible.

Downstream Processes: These processes take place after the lift is sold and installed and are no longer under the control of the manufacturing industry, but by the product owner.

-   Lift use.
-   Lift maintenance: Spare parts, use of consumables (e.g. lubricants), and displacement of lift workers to the lift installation. The later was left outside the system boundaries in this study, but should be considered when assessing different technologies.
-   Lift modernisation. Excluded from the boundaries of an LCA because it depends on the user decision and the information is therefore unknown to the LCA practitioner
-   Lift dismantling.
-   Lift disposal or end-of-life. Collection and transport of the complete lift to the end-of-life treatment facilities and corresponding treatment. Conversion into recycled material was excluded.

3   LCA RESULTS, INTERPRETATION AND RECOMMENDATIONS.

As mentioned in 2.1, the purpose of the study was to identify the most significant aspects of the lift product system with view to define a suitable LCA method that supported Product Category Rules. This objective was achieved. Annex B of [10], indicates the degree of completeness of the lift inventories used. As the results were not intended to be used in comparative assertions disclosed to the public, no uncertainty analysis[3] was conducted. The results of the LCA were calculated for different impact categories and eco-indicators. Most of the results presented in the following sections

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[2] This transport of the product to the consumer is a downstream process in the case of small goods.
[3] Quantification of the uncertainty introduced into the results of the analysis due to the cumulative effects of model imprecision, uncertainty of the inputs and the variability of the data.

are expressed in units of Eco-Indicator 99 [17], because this end-point indicator aggregates different environmental categories in a single value and makes it easier to see general tendencies. Although no official critical review was arranged, the doctoral thesis in which this complete study has been published was reviewed by several renowned international experts [10]. This section summarizes the conclusions reached after the sensitivity analysis performed. These are the aspects, architects and lift consultants need to pay attention to when interpreting the environmental data provided by a lift supplier for selecting the most environmental friendly option for an application.

3.1   Lifts materials composition and manufacturing processes

Table 1 and Table 2 show the lift composition of a 630 kg geared traction lift in weight. The highest percentage corresponds to metal parts, which are recyclable or contain recycled materials, however the impact of electric and electronic components, which average for less than 2% in weight, represent a much higher % of the total impact of the materials phase. For eco-indicators/impact categories that consider more aspects than the consumption of fossil resources or global warming potential, components like the control cabinet are among, or even the most relevant (see Table 3).

Table 1: Distribution by material

Type of material	% weight
Ferrous Metals	85,72%
Non Ferrous Metals	2,10%
Polymers	1,52%
Elastomers	0,12%
Gases and fluids	0,05%
Modified organic natural materials	0,34%
Paintings and superficial Coatings	0,30%
Electronic components	1,93%
Inorganic materials	0,30%
Adhesives	0,04%
Packaging	7,58%

Table 2: Distribution by functional group

Components	% weight
Traction unit (Electric Driver)	6,02%
Anti-fall safety devices	1,18%
Controller cabinet	2,32%
Components of the elect. installation	2,28%
Landing doors	10,54%
Car doors	1,58%
Car frame (sling)	7,72%
Counterweight frame (sling)	23,10%
Car	8,12%
Car guide rails	17,56%
Counterweight guide rails	10,23%
Suspension and compensation ropes	1,52%
Fixing elements	0,18%
Packaging	7,59%
Well components	0,05%

Table 3: Environmental impacts of the materials phase depending on the functional group

		EcoIndicator 99 (E/E)		Global Warming Potential		Ozone Depletion Potential		Acidification Potential		Eutrophication Potential		Photochemical Ozone Creation Potential	
		Pts	%	Kg CO2 -eq	%	Kg CFC- 11-eq	%	Kg SO2 -eq	%	Kg PO4-eq	%	Kg C2H4-eq	%
GROUP 1	Traction Unit (Electric Driver)	118,77	12,25%	553,35	8,09%	5,23E-05	9,74%	4,25	11,97%	3,47	13,45%	3,12E-01	8,97%
GROUP 2	Overspeed Governor	4,88	0,50%	58,90	0,86%	2,54E-06	0,47%	0,22	0,62%	0,12	0,47%	3,30E-02	0,95%
GROUP 3	Controller cabinet	155,28	16,01%	544,49	7,96%	4,86E-05	9,06%	4,84	13,63%	5,70	22,13%	2,41E-01	6,93%
GROUP 4	Travelling cables	146,30	15,09%	225,87	3,30%	1,14E-05	2,12%	4,36	12,26%	4,57	17,76%	1,94E-01	5,58%
GROUP 5	Car operator panel	23,33	2,41%	74,15	1,08%	6,53E-06	1,22%	0,59	1,67%	0,53	2,07%	3,17E-02	0,91%
GROUP 6	Landing operator panel / Call indicator board	4,80	0,50%	26,02	0,38%	2,19E-06	0,41%	0,15	0,42%	0,10	0,37%	8,68E-03	0,25%
GROUP 7	Door front/frame/liner (sheets)	3,82	0,39%	13,54	0,20%	9,24E-07	0,17%	0,07	0,20%	0,02	0,10%	4,23E-03	0,12%
GROUP 8	Landing Doors	72,07	7,43%	884,20	12,93%	1,54E-04	28,73%	3,44	9,67%	1,79	6,94%	4,31E-01	12,41%
GROUP 9	Doors operators	36,47	3,76%	256,65	3,75%	2,20E-05	4,09%	1,30	3,66%	1,39	5,41%	1,02E-01	2,94%
GROUP 10	Car doors	34,85	3,59%	123,44	1,80%	8,25E-06	1,54%	0,64	1,80%	0,22	0,87%	3,84E-02	1,11%
GROUP 11	Car Frame + Counterweight frame + Fixing Parts + Bed Plate + Well components	72,74	7,50%	862,34	12,61%	4,31E-05	8,04%	3,14	8,85%	1,70	6,58%	4,52E-01	13,02%
GROUP 12	Car	108,44	11,18%	954,07	13,95%	6,89E-05	12,84%	4,44	12,48%	1,59	6,18%	4,09E-01	11,79%
GROUP 13	Guide Rails	148,17	15,28%	1.856,23	27,14%	8,97E-05	16,71%	6,40	18,00%	3,92	15,24%	1,02E+00	29,27%
GROUP 14	Mechanical parts (Accessories + Fixing Parts + Other Components)	18,26	1,88%	193,82	2,83%	1,14E-05	2,12%	0,73	2,04%	0,31	1,21%	1,04E-01	2,99%
GROUP 15	Suspension Ropes	12,19	1,26%	134,08	1,96%	7,53E-06	1,40%	0,51	1,44%	0,12	0,46%	7,21E-02	2,08%
GROUP 16	Governor Ropes	0,91	0,09%	10,00	0,15%	5,62E-07	0,10%	0,04	0,11%	0,01	0,03%	5,38E-03	0,16%
GROUP 17	Counterweigh Weights	8,46	0,87%	69,32	1,01%	6,71E-06	1,25%	0,43	1,20%	0,19	0,73%	1,74E-02	0,50%
Total		969,75		6.840,45		5,37E-04		35,54		25,76		3,47	

Although the completeness of the inventory data regarding the manufacturing processes is far from being ideal, the screening studies showed that their ecological relevance is low (see Figure 1).

📖 Attention shall be paid to the fact that electronic components introduced to improve the lift performance during the usage phase may significantly worsen the materials phase.

📖 The cut-off rules applied for the inventory shall be declared by the practitioner to avoid that materials with a high environmental relevance be excluded.

3.2   Relevance of the usage phase

This is the most critical phase in the LCA of a lift because of the difficulty to predict it. The results are therefore highly sensitive to the method selected for the estimation of the energy consumption and the assumptions made regarding the usage of the equipment, which determine the time distribution of the running and non-running periods. Figure 1 shows the results of the complete LCA of one of the lifts described in Annex B of [10]. The different columns show the environmental impact of the lift system during its whole life (estimated as 20 years) measured in units of Eco-indicator 99 for the five usage categories defined in VDI 4701-Part 1 [18] and the 5 first categories of ISO 25745-2 [1]. Whereas VDI usage categories are based on building characteristics that may be ambiguous and in the practical application cause that two different usage categories can be possible for the same application, ISO 25745-2 [1] defines the usage categories according to the daily number of starts (a parameter, which is already used in the sector as a measure of the intensity of travel for selecting the best equipment) and gives average values, based on thousands of simulations, for the distance travelled, the weight transported and the time spent in the different operational modes.

The German guideline was before ISO 25745-2 the only document providing usage tables with data of average time spent by the lift in the different operating conditions and has been, for this reason, the reference document used by LCA practitioners in the lift industry till now. Although VDI is a good guideline for comparison of products, its approach is not adequate for LCA because it considers the ISO 25745-1 reference cycle (a lift travelling with rated load over the full building height). Thus, if these data (load and distance) are multiplied by the number of starts, it will result in the lift travelling longer and carrying a higher load than it actually does. This might not have a high impact in the

average energy consumption (in some cases; in others it does), but when calculating the environmental performance of the lift system per functional unit Pkm (see 2.2.2), the higher denominator will reduce the environmental impact. Another flaw of VDI-Part 1 is that energy consumption in idle is not considered (Part 2 [19] does), what results in an important underestimation of the total standing energy consumption (idle power is always higher than standby) for the highest usage categories, as in these cases the lift has not time to switch into $standby_{5min}$ (5 minutes have elapsed since the last trip) during the normal operation period [9,10].

As per the results shown in Figure 1, the environmental impact associated to the use phase of this lift only exceeds the impact of the lift materials in categories 3 (for VDI), 4 and 5, while it is lower for categories 1, 2 and 3 (for ISO). Both for the VDI and ISO usage categories, the energy consumption travelling generates a greater environmental impact than the standby phase in categories 3, 4 and 5, but not in the low demand case. It is important to remark here, that due to the absence of measured data, the same value has been used for the idle and $standby_{5min}$ power and that this lift does not have a further saving mode ($standby_{30min}$). The spare parts have been estimated according to the preventive maintenance plan. Thus, the conclusions for Usage category 3 could change if the actual idle power and more accurate data of the spare parts were considered. In Table 4, the results of Figure 1 are grouped in the two most relevant aspects: Lift composition (Materials + spare parts) and usage (aggregating running, idle = $Standby_{5min}$ and $Standby_{5min}$). The Nr. of starts for the VDI usage categories have been obtained from the travelling time given in the tables, considering that each cycle is the ISO 25745-1 ref cycle (full rise).
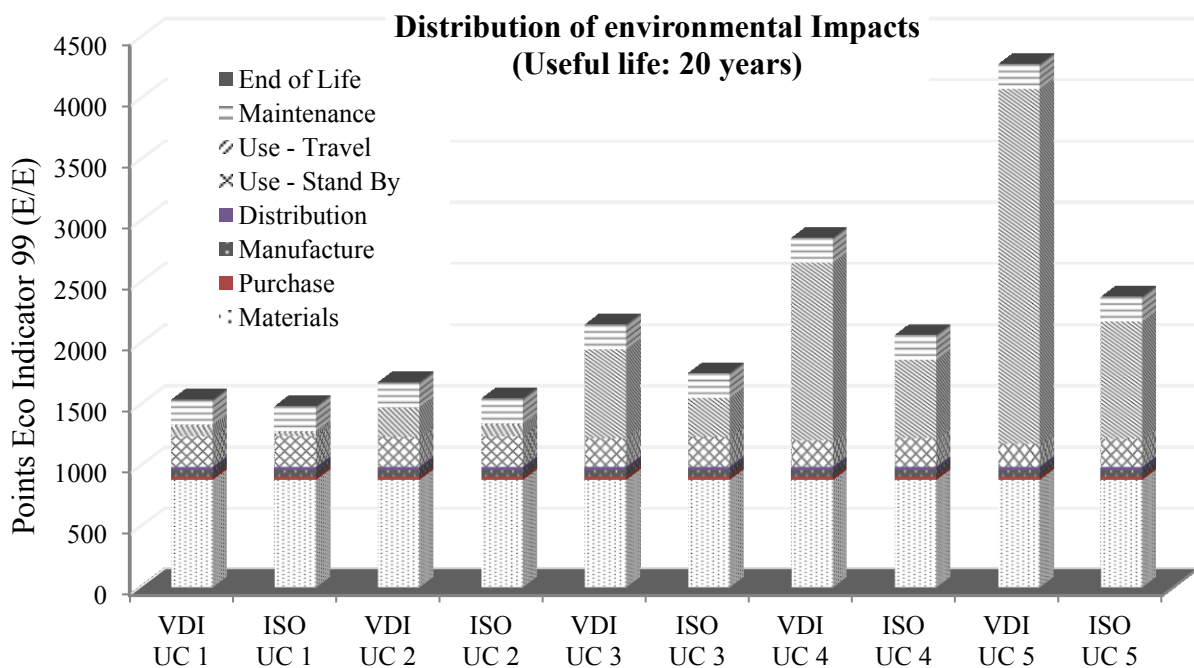
Figure 1: Environmental Impact results 630 Kg gearless traction based on usage of the facility

Table 4: Impacts in different life cycle phases (grouped). Travelling times and Nr. of Starts

Usage Cat.	Eco Indicator 99 (E/E)									
	1		2		3		4		5	
Method	VDI	ISO	VDI	ISO	VDI	ISO	VDI	ISO	VDI	ISO[4]
Materials + Spare parts	**70,48%**	**73,00%**	**64,53%**	**70,05%**	**50,36%**	**61,75%**	**37,89%**	**52,44%**	**25,33%**	**45,56%**
Use (Travel + Standby)	**22,55%**	**19,79%**	**29,09%**	**23,02%**	**44,66%**	**32,14%**	**58,37%**	**42,38%**	**72,16%**	**49,93%**
Manufacture	3,52%	3,65%	3,23%	3,50%	2,52%	3,09%	1,89%	2,62%	1,27%	2,28%
Purchase	1,84%	1,90%	1,68%	1,82%	1,31%	1,61%	0,99%	1,37%	0,66%	1,19%
Distribution	1,61%	1,66%	1,47%	1,60%	1,15%	1,41%	0,86%	1,19%	0,58%	1,04%
End of Life	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Travel time (h)	0,20	0,09	0,50	0,22	1,50	0,66	3,00	1,32	6,00	1,98
Standby time (h)	23,80	23,91	23,50	23,78	22,50	23,34	21,00	22,68	18,00	22,02
Starts/day	77		192		576		1152		2304	

📖 These results show that, unlike often believed in the lift industry, the usage phase is not always the most relevant, in line with some statements made by some hydraulic lift manufacturers [20] and [21].

📖 The estimation of spare parts and preventive maintenance operations (which will affect the transportation of lift workers) shall be in accordance with the different categories of usage, as the life of the components depends on the lift activity (Nr. of starts) and lift technology considered.

Table 5 shows the difference between running and non-running times considered by VDI-1 and ISO 25745-2, which are the source of the big differences in the highest usage categories.

Table 5: Time spent travelling and standing (ISO includes idle, Stby$_{5min}$ and Stby$_{30min}$)
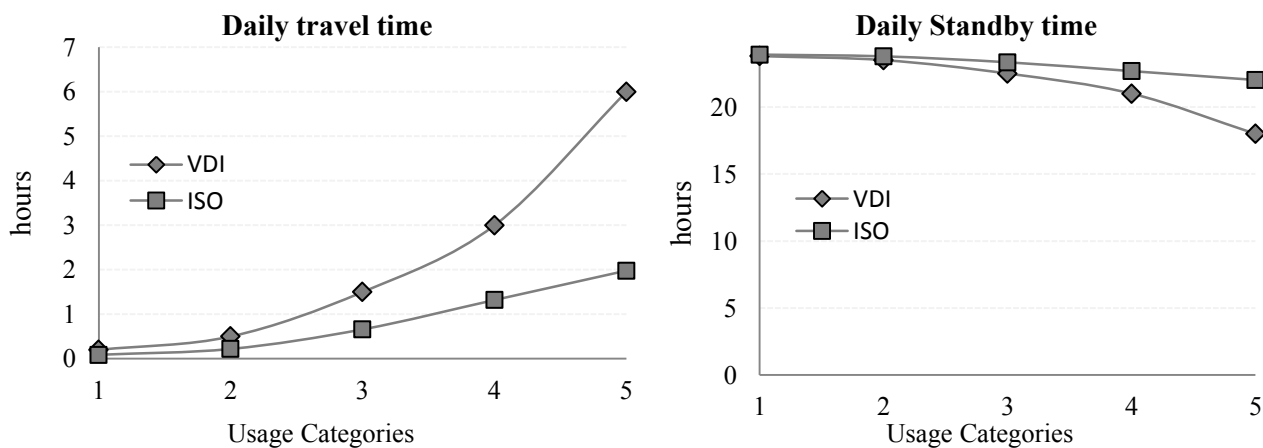
3.3 Influence of the energy mix

The environmental impact of the different power generation technologies (hydropower, nuclear, coal, gas and other fuels, combined cycle, wind, solar, cogeneration, biomass, bio-fuels, etc.) vary substantially. Eco-Indicator 99, for example, strongly penalizes electricity generation technologies

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[4] ISO 25745-2 considers a 6th usage category not represented in the graph to be coherent with VDI.

which are very natural resource-intensive and produce air emissions, but ignores the high risk of a worst case scenario and the existence of waste for which treatment is not yet possible, in the case of nuclear energy. Thus, countries or companies using a higher proportion of renewable or clean production technologies will reduce the impact generated by their energy-consuming processes and products. In the same way, lifts installed in countries with a good energy mix will be more environmentally friendly. Figure 2 below shows possible environmental impact scenarios for a traction lift installed in different countries. The energy mix assumed corresponds to year 2008.

Environmental Impact depending on the Country mix - Usage Category 3
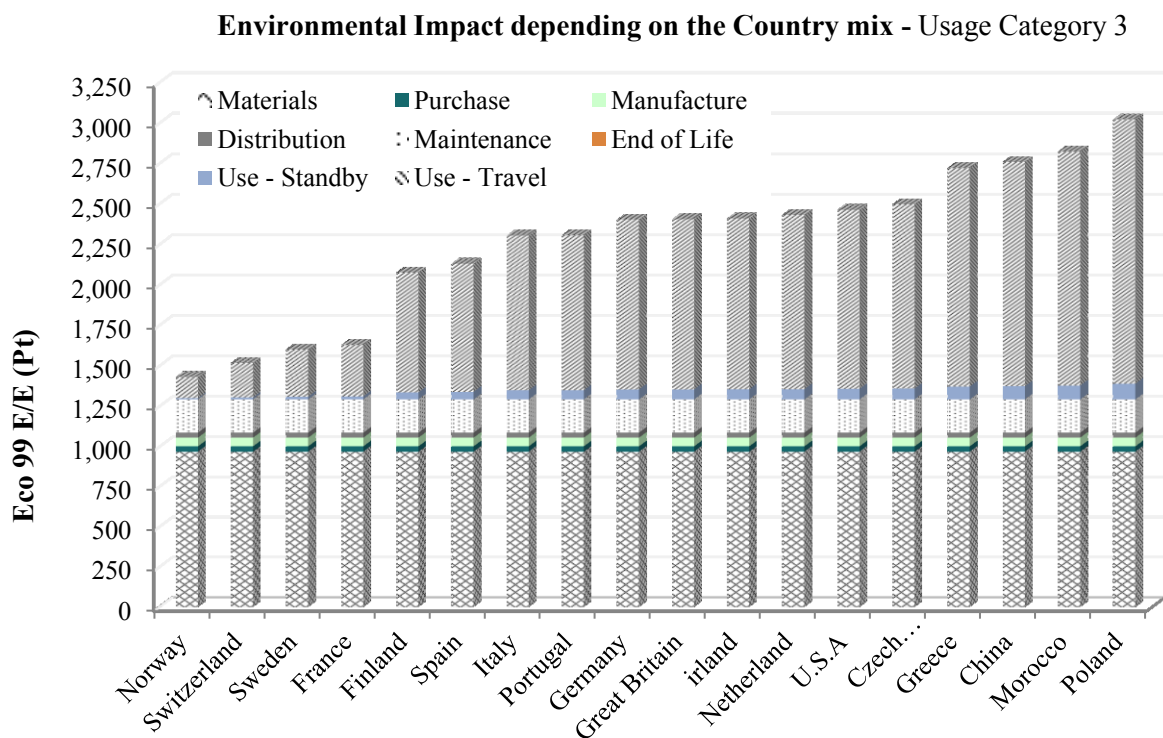
Figure 2: Environmental Impact results (630kg gearless traction) for the usage category 3, installed in different countries

📖 The strong influence of the energy mix in the results of LCAs suggests that it might be reasonable to consider the kWh as unit for assessment of energy consumption for lift comparison purposes. In any case, LCA data for publication should clearly indicate what mix has been used for the assessment.

3.4   Maintenance phase: replacements and repairs

The results of the LCA are very sensitive to the amount of spare parts that, according to the estimation of the lift designer will be consumed during the useful life of the product for ensuring a good performance. This can be a deciding argument for selecting a certain lift technology

📖 The lift user shall be informed about the necessary preventive maintenance operations and replacements necessary to guarantee the best product performance. These replacements shall be accounted as material inputs for the LCA. The preventive maintenance operations will depend on the lift usage and its expected life and may therefore differ between usage categories and technologies.

3.5   Modernisation

Modernisation operations are quite common in the lift sector. They increase the environmental burden of the lifts components phase, making their contribution to the total impact become more relevant. If the substitution implies a technological improvement which optimizes the energy consumption, the use phase will also be affected.

📖 Although lift modernisations are excluded from life cycle assessments because they are not under the control of the lift company selling the product and are not predictable; from an environmental perspective it is advisable that the impact caused by the upgraded components be checked against the environmental improvement achieved.

3.6   Lift logistics

The influence of logistic processes in the environmental impact is sensitive to changes related to the lift supply chain (components set up) and to the transportation method selected (the environmental impact of transporting 1 ton of material along 1 km is very different depending on whether the product travels by rail, truck, ship or a cargo plane). For this reason, logistics are usually only analysed in LCAs for companies' internal use [10]. In the case of LCAs for public assertions, it is common to use average logistic values. Obviously, the distribution phase will be more relevant for companies serving international markets.

3.7   Influence of end of life treatments

As explained before, at the time of conducting the first study no detailed information about the lift waste management was available, for which reason it was estimated that the lift was disposed in the landfill. However, this seems not reasonable, as by judicious management of recyclable materials a significant improvement in the environmental performance of the components can be achieved. In general, the end of life phase is very sensitive to the end of life scenario assumed; i.e., to whether materials are reused, recovered or recycled and to which phase of the life cycle these impacts are allocated. In the first study, a possible configuration of municipal waste management was modelled in Simapro [22]. Environmental credits were given to all recycled materials obtained. This resulted in a reduction of 20% of the environmental impact. In the second study, the recyclability of the lift was analysed following the standards of the rail industry [23]. The results revealed that in a lift, whose components could be 100% disassembled, 99% (weight) of the materials could be recycled, 0,5 % valorised (for energy recovery) and approximately other 0,5% would be waste.

📖 In order to improve the lifts end of life management, lift owners should be provided with indications regarding how to conduct the dismantling operations and with information about the best possible treatment options for each component and their potential recycling and recovery rate.

3.8   Influence of the estimated useful life

Being the lift a EuP (Energy using Product), the duration of its useful life will determine the amount of energy consumed and maintenance operations necessary. There is currently no consensus in the lift sector about an average useful life of lifts, mainly because of the continuous modernisations works that are undertaken to improve their performance. It would be interesting to count with some statistics from the sector. Till then, the lift user shall pay attention to the useful life guaranteed by the lift manufacturer and estimated in the LCA. A reduction of the useful life increases the relevance of the materials phase whereas the opposite decreases it. The estimation of spare parts and maintenance operations shall be recalculated accordingly.

📖 The life expected for the lift and/or their components plays a decisive role in the final environmental impact of the lift. Especially in the materials phase, but indirectly affecting also the usage phase (maintenance and energy consumption). Wear of the installation may lead to higher consumption. Better quality may imply lower environmental impact.

3.9   Influence of data bases used

For all background processes, the selection of the databases and processes of the databases is of decisive relevance, because not all of them have the same level of quality and accuracy.

 Common databases for background data should be provided by the lift industry to enhance the transparency with view to comparison.

3.10 Influence of the environmental categories considered or the eco-indicators used

The environmental impact categories considered for the assessment can change the distribution of environmental loads attributable to the different components or phases of the life cycle. Some materials or processes, which are not responsible for a high amount of emissions, can however cause other damages to the health. For this reason, it is always recommended to use more than one environmental categories and assessment methods for a right interpretation of the results of an LCA.

 The uncertainty of the results associated to the databases, environmental categories considered or assessment methods employed can be avoided if these are fixed in the Product Category rules.

3.11 Important remarks

An environmental declaration can be used to select the best lift product or the best lift supplier, installer, etc., for a particular application, where more technologies and/or manufacturers are competing. In this case, the LCA practitioner shall use all actual data available directly applicable to the particular case considered: from suppliers, manufacturing processes, energy mix in the production facilities, etc., as well as the circumstances of the location where the product will be used. Generic data should only be used when some of this information is not available, unless otherwise stated.

However, when the results of a LCA are used in another context, for example in the design phase of a model lift or to check what technology (hydraulic/electrical, regenerative/non-regenerative, etc.) is more suitable for a certain application (big/small residential or office buildings, hospitals, etc.), generic data shall be preferably used for the assessment, so as to minimise the risk that aspects not related to the technology affect the results.

Some examples of foreground data which can make a significant difference in the results are:

- Company specific energy mix used in the manufacturing phase.
- Use of fresh water resources.
- information on local/site-specific impacts (acidification, eutrophication and biodiversity),
- self-production of components or concentration of suppliers customers etc., affecting logistic data
- the use of materials or processes not included in common databases
- the use different secondary materials with respect to the ones listed in in common databases
- much higher or much lower environmental impact than reported in background databases due to the application of green purchasing policies (environmental friendly suppliers),
- a better end of life treatment

In general, better environmental performance than average of the sector or the figures given in a standard, guideline or future Product category rules.

4   CONCLUSIONS AND FURTHER WORK

LCA Practitioners and users are often concerned about the quality of the environmental results provided in public assertions. The absence of information regarding the application of the LCA methodology, the imprecision of the system boundaries used in the analysis, the use of background data from different sources, different assessment methods or indicators, etc. cause that equally credible analyses can produce qualitatively different results, thus leading to varying interpretations. This undermines the reliability of environmental assessments from a scientific point of view, and renders them ill-suited for eco-labelling. In this paper, the LCA results of an example lift have been used to illustrate what the key aspects to be considered in the assessment are, but as already suggested

in [10], a harmonisation process is needed in the lift industry. Some efforts have already started. It is important, that all relevant stakeholders are involved in the consultation phase of the Product category rules that are been developed [15].

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BIOGRAPHICAL DETAILS

Dr. Ana Mª Lorente Lafuente has been an Industrial Engineer since 1994 and holds a PhD. in Mechanical engineering from the University of Zaragoza since 2013. She is member of the ISO/TC178/WG10 since 2009 representing AENOR as technical expert. After twelve years of professional activity in the private sector, which included the lift company Wittur A.G, the author joined the department for development of mechatronic products of ITA in 2006. In 2011 the author moved to Germany and is currently working at the Institute of Technical Thermodynamics of RWTH Aachen University (Germany) with a scholarship from the Institute for Advanced Sustainability Studies in Potsdam.

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- Product Category Rules proposal for conducting comparable LCAs and issue of Type III environmental Statements

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Lift system calculations in EN 81-50

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Abstract. Lift engineers responsible for the design of lift systems conforming to EN 81-1 should be conversant with the equations for guide rails, rope traction and rope factor of safety in that standard. The new EN 81-20 references EN 81-50 which now includes such equations, with some minor changes, and some additional helpful guidance.

Despite the apparent complexity of these equations, making calculations need not be a daunting prospect. The use of manual or spreadsheet methods are valuable in gaining an engineering appreciation for these calculations. Such an appreciation is important in interpreting the results obtained from software packages and might not be gained simply by "plugging in" numbers. The use of such software packages (which might not be infallible or which might incorporate assumptions not clear to the user) should be subject to verification; one method is comparison with manual calculations.

This paper looks at the main changes in the calculations for guide rails, rope traction and rope factor of safety and through examples provides a means to assess the implications of these changes.

The paper also reflects on some underlying assumptions in these equations and some engineering implications from their use. Implications for conformity with the new standards will be touched-on. Future directions for the development of the standards will be mentioned.

1. INTRODUCTION

For many years EN 81-1 [1] and EN 81-2 [2] have been the standards to which many new traction and hydraulic lifts have been designed. These standards, after a period of co-existence with the new standards EN 81-20 [3] and EN 81-50 [4], will be withdrawn. The normative requirements for both traction and hydraulic lifts are to be found in EN 81-20 while other requirements, including for elements of lift system calculations, are to be found in EN 81-50. The calculations in EN 81-50 are referenced from EN 81-20 so these elements of EN 81-20 are also applicable.

This paper looks at the calculations in EN 81-50 and how these have changed from those in EN 81-1 and EN 81-2. The clauses within EN 81-20 and the calculations in EN 81-50 which they reference are reviewed and compared with their predecessors in EN 81-1 and EN 81-2. For calculations for guide rails, rope traction and rope factor of safety, sample calculations are presented which illustrate the changes made.

The introduction of EN 81-1 and EN 81-2 in 1998 came at a time when much more use was being made of software packages to make lift system calculations[1]. The use of proprietary software packages or the use of spreadsheets allowed rapid calculation which was an aid to more optimal design and selection of components.

However, the use of such packages, especially those whose underlying equations and assumptions are not transparent to the user, raise issues which need to be considered by users:

- Simply taking the lift parameters and "plugging in" these numbers is less likely to promote an appreciation of the fundamentals than would be gained through making manual calculations or even implementing these on a spreadsheet.

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[1] Calculations for the system torque are not included within either EN 81-1 or EN 81-20.

- Without such an appreciation, the output from software packages might not be scrutinized so critically and errors or opportunities for improvement might not be identified by the user.

- Most lift designers inevitably now have quality systems and certification to relevant standards such as ISO 9000, possibly supplemented by other requirements such as those imposed by the EC Lifts Directive. The results of any engineering calculations should be checked. One method of verifying the correct operation or "calibration" of software packages is by the comparison of their results with the results of manual calculations.

2. PARAMETERS USED FOR CALCULATION

The parameters of two lift configuations which are the subjects of calculation in this paper are tabulated below. Table 1 lists parameters for a conventionally guided situation where it is assumed the line of suspension, centre lines of the guides and centre of the lift car are all coincident. Table 2 lists parameters for a cantilever guided situation suspended from point **s** in the figure in Table 2, reproduced from G.7.4 of EN 81-1 [1]. The parameters listed in Table 2 are those which differ from those in Table 1 owing to the different guidance; parameters for suspension and traction are common to both configurations should be taken from Table 1. All symbols are as used in EN 81-20 [3] and EN 81-50 [4]. There is no compensation included.

Table 1: Key parameters for conventionally guided configuration

Parameter	Value	Parameter	Value
Distance between guide fixings, l	4000 mm	Traction sheave angle of wrap, α	3.14 rad
Car guide rails (ISO 7465)	T127-1/B	Traction sheave groove	Undercut V
Tensile strength of guide rails, R_m	370 N/mm^2	Groove angle (50°), γ	0.87 rad
Overall height of guide rails	20 m	Undercut angle (105°), β	1.83 rad
Car size: D_x	1400 mm	Rated speed of lift	1 m/s
D_y	1600 mm	Reeving ratio	2:1
Rated load, Q	1000 kg	Traction sheave diameter, D_t	320 mm
Number of car guides, n	2	Divertor pulley diameters, D_p	320 mm
Empty car weight, P	1250 kg	Reduced mass of a pulley	30 kg
Distance between guide shoes, h	2800 mm	No. pulleys on car side	2
Safety gear impact factor, k_l	3	No. pulleys counterweight side	1
Dimensions x_p, y_p	0	Rope diamter, d_r	8 mm
Acceleration due to gravity, g$_n$	9.81 m/s^2	Mass of ropes on one fall, M_{SR}	25 kg
π	3.14	Mass of travelling cables, M_{TRAV}	12 kg
Note: guide rail parameters from ISO 7465 [5].		Counterweight balance factor	0.45

Table 2: Key parameters for cantilever guided configuation differing from Table 1

Parameter	Value
Distance between guide fixings, l	2500 mm
Car guide rails (ISO 7465)	T127-1/B
Car size: D_x	1100 mm
D_y	2100mm
Distance from guides to car wall, c	200 mm
Distance between guide shoes, h	2800 mm
Dimensions x_p, y_p	500 mm; 0 mm

3. GUIDE RAIL CALCULATIONS

EN 81-1 [1] includes normative requirements for the maximum permissible stresses and for guide rail deflections with a calculation method for forces, stresses and deflection in *informative* Annex G. EN 81-20 [3] has normative requirements generally as EN 81-1 except for the following additions.

- There is a requirement to consider the combination of deflections of guide rails, brackets, play in the guide shoes and straightness of the guide rails which must be taken into account in order to ensure a safe operation of the lift. In cases where previously no allowance was made for deflection of these additional elements, then guide rail selections and maximum fixing intervals may need to be revised.

- Equations for vertical loads include self-weight of guides and push-through force of clips (for longer travels or where building settlement is significant) are included as *normative* requirements. Depending on the travel of the lift and the pull-through force of guide clips, the additional vertical load could be significant and require a review of buckling calculations.

- EN 81-20 requires that guide rails to be calculated according to one of:
  a) EN 81-50, 5.10; or
  b) EN 1993-1-1; or
  c) Finite Element Method (FEM).
  So it is now a *normative* requirement to use one of these methods. While the latter two methods might provide useful alternatives, the discussion here focuses on 5.10 of EN 81-50.

EN 81-50 [4] clause 5.10 has equations generally as EN 81-1 Annex G for calculating bending and buckling stresses, and deflections. It includes an additional equation for evaluating flange bending with sliding shoes. EN 81-50 Annex C is informative and has an example for calculation based on the general case and not including a number of different configurations as in EN 81-1 Annex G. These calculations are to demonstrate the adequacy of a known design solution including guide size, number or guides and fixing interval.

The following are calculations for the two configurations in Tables 1 and 2. In each case, only the worst case situation is calculated for the car guide rails i.e. for the engagement of the safety gears. Depending on the nature of the application, it might be that safety gear operation is not the worst case situation for conformity as the level of permitted stress is lower for normal running. To demonstrate conformity, all loading situations should be calculated and checked to be within the relevant permitted stress for all guide rails used.

3.1 Sample calculations - conventionally guided configuration as Table 1

From EN 81-20, 5.7.2.3.5, the vertical force, F_v, for the car guides, where M_g is the self-weight of the guide rails and F_p is the push through force from guide clips which will be neglected here, is:

$$F_v = \frac{k_1 g_n (P+Q)}{n} + \left(M_g g_n\right) + F_p. \tag{1}$$

Which can be evaluated as:

$$F_v = 3x9.81x(1250 + 1000)/2 + (17.85x20x9.81) = 36611 \text{ N}.$$

To calculate the buckling stress, σ_k, 5.10.3 of EN 81-50, like EN 81-1, uses the "omega method", ω, (although it does not retain the tables of EN 81-1 Annex G so values need to be calculated). This is based on the slenderness ratio, λ; the ratio of the distance between the guide rail fixings and the lesser of the two radii of gyration of the guide rail:

$$\lambda = \frac{l_k}{i} = 4000/23.61 = 169.4. \tag{2}$$

From 5.10.3 of EN 81-50, for R_m=370 N/mm^2 and for $115 < \lambda \le 250$, ω=0.00016887λ^2 = 4.85. (3)

$$\sigma_k = \frac{(F_v + k_3 M_{aux})\omega}{A} \tag{4}$$

M_{aux} and k_3 are the weights of auxiliary equipment and relevant impact factor which will be assumed to be zero here (although in many cases there are loads supported by the guide rails as in the case of many machine room-less designs). Then:

$\sigma_k = (36611 \times 4.85)/2274 = 78$ N/mm^2

The calculation of bending loads for safety gear operation is included in C.2 of informative Annex C of EN 81-50 which illustrates the evaluation of worst case bending stress owing to the car load being offset relative to the x-axis (case 1) and y-axis (case 2).

$$F_x = \frac{k_1 g_n (Q x_q + P x_p)}{nh}. \tag{5}$$

$$F_y = \frac{k_1 g_n (Q y_q + P y_p)}{\left(\frac{n}{2}\right)h}. \tag{6}$$

Combining the equations for M_y and σ_y to give the bending stress relative to the y axis:

$$\sigma_y = \frac{3F_x l}{16W_y} \tag{7}$$

Similarly for the bending stress relative to the x axis, σ_x:

$$\sigma_x = \frac{3F_y l}{16W_x} \tag{8}$$

For case 1 relative to the x-axis, $x_q = D_x/8 = 175$ mm and $y_q = 0$ so $F_{x(1)}$ and $F_{y(1)}$ can be evaluated using these and equations (5) and (6):

$F_{x(1)} = \frac{3 \times g_n (1000 \times 175)}{2 \times 2800} = 920$ N and $\sigma_{y(1)} = \frac{3 \times 920 \times 4000}{16 \times 23610} = 29$ N/mm^2

$F_{y(1)} = 0$ and $\sigma_{x(1)} = 0$

For case 2 relative to the y-axis, $x_q = 0$ and $y_q = D_y/8 = 200$ mm so $F_{x(2)}$ and $F_{y(2)}$ can be evaluated in a similar way:

$F_{x(2)} = 0$ and $\sigma_{y(2)} = 0$

$F_{y(2)} = \frac{3 \times g_n (1000 \times 200)}{2800} = 2102$ N and $\sigma_{x(2)} = \frac{3 \times 2102 \times 4000}{16 \times 30650} = 51$ N/mm^2

The combined bending stress, σ_m, is

$$\sigma_m = \sigma_x + \sigma_y. \tag{9}$$

This has its worst case value for case 2 where $\sigma_m = 51$ N/mm^2

The worst case combined bending and compressive stress is:

$$\sigma = \sigma_m + \frac{(F_v + k_3 M_{aux})}{A}. \tag{10}$$

Evaluating this: $\sigma = 51 + \frac{(36611)}{2274} = 67$ N/mm^2

The combined bending and buckling stress is:

$$\sigma = \sigma_k + 0.9\sigma_m. \tag{11}$$

Evaluating this: $\sigma = 82 + 0.9 \times 51 = 128$ N/mm^2

None of these combined stresses are close to the permitted stress of 205 N/mm^2 (for steel of R_m =370 and safety factor of 1.8 for safety gear operation). All looks well so far except that the flange bending stress and guide rail deflections have not been calculated.

Equations for guide rail deflections in 5.10.6 of EN 81-50 are:

$$\delta_x = 0.7\frac{F_x l^3}{48EI_y} + \delta_{str-x}.$$
(12)

$$\delta_y = 0.7\frac{F_y l^3}{48EI_x} + \delta_{str-y}.$$
(13)

These can be evaluated as:

$$\delta_x = 0.7\frac{920x4000^3}{48x207000x1499000} + \delta_{str-x} = 2.8 \text{ mm} + \delta_{str-x}$$

$$\delta_y = 0.7\frac{2102x4000^3}{48x207000x1879000} + \delta_{str-y} = 5.0 \text{ mm} + \delta_{str-y}$$

So the deflection in the y direction, while it might have been close to being considered in conformity with EN 81-1, is excessive if some deflection of the structure and guide brackets is taken into account. Clearly this needs to be established and the contribution of the guide deflection reduced to keep the overall deflection within 5 mm. Since the geometry of the arrangement is balanced, this would require measures such as reduced distance between guide fixings, larger guide section or a switch to a safety gear with a lower impact factor i.e. to progressive safety gear.

3.2 Sample calculations - cantilever guided configuration as Table 2

The evaluation of forces, stresses and deflection for the cantilever guided arrangement is with the same equations as for the conventionally guided configuration. Only the vertical forces remain the same; the horizontal forces are significantly different and are evaluated as follows.

As noted, the parameters in equations (1) are unchanged so $F_v = 36611$ N.

Using equation (2) with the smaller distance between guide fixings: $\lambda = \frac{l_k}{i} = 2500/23.61 = 106$

Similarly to before from 5.10.3 of EN 81-50 but with $85 < \lambda \le 115$, $\omega = 0.00001711\lambda^{2.35} + 1.04 = 2.02$

Similarly to equation (3), $\sigma_k = (36611\text{x}2.02)/2274 = 33 \text{ N/mm}^2$

For the calculation of bending loads, there will be much larger values for F_x than for the conventionally guided configuration (since both the empty car weight and car loads are offset significantly from the guide rails). Using equations (5) to (8) and for the two loading cases, the bending loads and stresses are as folows.

For case 1 relative to the x-axis, $x_q = c+5D_x/8 = 888$ mm, $x_p = 500$ mm; $y_q = 0$ and $y_p = 0$. So $F_{x(1)}$ and $F_{y(1)}$ can be evaluated using these and equations (5) and (6):

$$F_{x(1)} = \frac{3xg_n(1000x888+1250x500)}{2x2800} = 7951 \text{ N and } \sigma_{y(1)} = \frac{3x7951x2500}{16x23610} = 158 \text{ N/mm}^2$$

$F_{y(1)} = 0$ and $\sigma_{x(1)} = 0$

For case 2 relative to the y-axis, $x_q = c+D_x/2 = 750$ mm, $x_p = 500$ mm; $y_q = D_y/8 = 263$ mm so $F_{x(2)}$ and $F_{y(2)}$ can be evaluated:

$$F_{x(2)} = \frac{3xg_n(1000x750+1250x500)}{2x2800} = 7226 \text{ N and } \sigma_{y(2)} = \frac{3x7226x2500}{16x23610} = 143 \text{ N/mm}^2$$

$$F_{y(2)} = \frac{3xg_n(1000x263)}{2800} = 2764 \text{ N and } \sigma_{x(2)} = \frac{3x2764x2500}{16x30650} = 42 \text{ N/mm}^2$$

The combined bending stress, σ_m, has its worst case value for case 2 where $\sigma_m = 185 \text{ N/mm}^2$

The combined bending and compressive stress, from (10) is: $\sigma = 185 + \frac{(36611)}{2274} = 201 \text{ N/mm}^2$

The combined bending and buckling stress is: $\sigma = 33 + 0.9\text{x}185 = 200 \text{ N/mm}^2$

All of these combined stresses are close to, but within, the permitted stress of 205 N/mm^2. From a conformity perspective, these are acceptable but might need to be reviewed in an engineering context. For instance, the assumptions made which underly the calculations should be reviewed to

make sure they are robust and can be controlled to be within the parameters used. From a practical perspective, any adverse variation in the distance between guide fixings (which can not always be so tightly controlled on site) would be likely to push guide stresses outside the permitted stress levels.

At this point, we should calculate the flange bending stress since the value of F_x is high (again from a strict conformity perspective, this should be done for all cases). EN 81-50, 5.10.5 gives two equations depending on the use of roller guide shoes (concentrated load) or sliding guide shoes:

$$\sigma_F = \frac{1.85 F_x}{c^2} \text{ for roller guide shoes} \tag{14}$$

$$\sigma_F = \frac{6 F_x (h_1 - b - f)}{c^2 (l + 2(h_1 - f))} \text{ for sliding guide shoes} \tag{15}$$

The dimensions introduced here are for the guide rail section: c is the thickness of the neck connecting the blade and the foot (not as dimension c in Table 2); h_1 is the guide rail height and f is foot depth of the where it connects to the blade. For T127-1/B guide rails, these dimensions are 10 mm, 89 mm and 11 mm respectively. b is half the width of the guide shoe lining and l is the length so depend on the type selected – we will assume 19 mm and 140 mm respectively.

Evaluating the flange bending stress using (14) and (15) with the worst case value for F_x:

$$\sigma_F = \frac{1.85 x 7951}{10^2} = 147 \text{ N/mm}^2 \text{ for roller guide shoes which is less than 205 N/mm}^2.$$

$$\sigma_F = \frac{6 x 7951 (89 - 19 - 11)}{10^2 (140 + 2(89 - 11))} = 96 \text{ N/mm}^2 \text{ for sliding guide shoes also less than 205 N/mm}^2.$$

Turning to the worst case deflections, these can be evaluated using (12) and (13) as:

$$\delta_x = 0.7 \frac{7951 x 2500^3}{48 x 207000 x 1499000} + \delta_{str-x} = 5.8 \text{ mm} + \delta_{str-x}$$

$$\delta_y = 0.7 \frac{2764 x 2500^3}{48 x 207000 x 1879000} + \delta_{str-y} = 1.6 \text{ mm} + \delta_{str-y}$$

So the deflection in the x-axis, irrespective of any allowance for the deflection of building structure and guide rails, is clearly excessive. In seeking to reduce this to acceptable limits, we can note that there are three alternatives:

1. Increase the guide section; this is likely to be be expensive and there might be implications for incorporating a larger guide section into the design;

2. Reduce the worst case value of F_x; as we saw above, this could be accomplished with a progressive safety gear reducing the value of k_1 to 2;

3. Reduce the distance between guide fixings, l. We can note that, because the deflection depends on l^3, a modest reduction in this dimension would bring about a significant reduction in deflection.

3.3 Further comment

A final observation on the two cases examined here is that in both cases, guide rail deflections have determined the design solution used. It is quite straightforward to rearrange (12) and (13) to arrive at equations for the minimum required second moments of area for the guide rail in a given design and hence make at least a first selection of a suitable guide rail for a given distance bewteen fixings.

4. ROPE TRACTION CALCULATIONS

EN 81-20, 5.5.3 [3] has normative requirements generally as those in EN 81-1 with a new possibility, in addition to rope slipping, of using an electric safety device to stop the machine to avoiding raising an empty car or counterweight. A note references calculation examples in 5.11 of EN 81-50; so their use is not a normative requirement of EN 81-20.

EN 81-50 clause 5.11 generally follows Annex M of EN 81-1 except for:
- need to lose traction for stalled car only where machine torque is sufficient to raise the car;
- emergency braking for reduced stroke buffers – acceleration rate to be sufficient to retard car and counterweight to speed for which buffers designed (EN 81-1 had 0.8 m/s/s).
- car and counterweight stalled for empty car at highest and lowest position (EN 81-1 based on worse case).

Equations for calculating applied traction ratios have some changes:
- correctly including successive rope falls after the first;
- correcting treatment of diverter and reeving pulleys;
- split into machine above and machine below;
- guidance including, if minimum friction forces cannot be ensured, deleting those terms.

Informative Annex D provides an example with simplified equations for that case.

4.1 Traction inequalities

The traction inequalities in 5.11.2 of EN 81-50 are as follows where T_1 and T_2 are the rope tensions on either side of the traction sheave and α is the angle of wrap around the traction sheave:

$$\frac{T_1}{T_2} \leq e^{f\alpha} \text{ for car loading and emergency braking.} \tag{16}$$

$$\frac{T_1}{T_2} \geq e^{f\alpha} \text{ for car/ counterweight stalled.} \tag{17}$$

The remainder of these sample calculations concentrate on what is often the worst case; satisfying the first inequality for emergency braking where there is a trade-off between roping and traction. This is not to lessen the importance of the car loading criteria or the second inequality but this can be readily calculated using the higher value for the coefficient of friction from EN 81-50, 5.11.2.2.2.

The first traction inequality has two sides; the first is the calculation of the applied traction ratio which depends on the suspended masses while the second is the calculation of the critical traction ratio which depends on the groove profile.

4.2 Example calculations – critical traction ratio

EN 81-50, 5.11.2.3 provides the equations to determine the friction factor, f, for the groove profile details in Table 1:

$$f = \mu \frac{4\left(1 - sin\frac{\beta}{2}\right)}{\pi - \beta - sin\beta} \text{ for unhardened undercut-V groove} \tag{18}$$

$$f = \mu \frac{1}{sin\frac{\gamma}{2}} \text{ for hardened V grooves} \tag{19}$$

The coefficient of friction for the emergency braking in EN 81-50 5.11.2.3.2 is dependent on the rope speed, v:

$$\mu = \frac{0.1}{1 + \frac{v}{10}}. \tag{20}$$

The value of μ can be readily calculated to be 0.083. Then from (18), f can be calculated to be 0.2 for an unhardened undercut-V groove with 105° undercut and from (19) also 0.2 for a hardened V groove with 50° angle. The value of the critical traction ratio can then be calculated from (16) as 1.87 for the emergency braking case. Note that the selection of groove parameters provides a similar critical traction ratio for either an unhardened groove with undercut V or for hardened V grooves.

Although a discussion of the coefficient of friction is outside the scope of this paper, the figures used in EN 81 are intended to be worst case and reflect those measured from oiled rope in traction

sheave groves. In normal operation, significantly higher values would be expected so the figures used in EN 81 incorporate some margin of safety.

4.3 Example calculations – applied traction ratio

At first sight the equations in 5.11.3 of EN 81-50 for the applied traction ratio look complex. However, they are for the general case so include for multiple reeving pulleys (m_{Pcar} and m_{Pcwt} are the reduced mass of pulleys on car and counterweight side respectively), all positions of the car in the well, the use of compensation, friction from the guide shoes etc. The following example follows the EN 81-50 Annex D equations for the emergency braking condition.

For the car with full load at the lowest landing:

$$\frac{T_1}{T_2} = \frac{(P+Q)(g_n+a)+2M_{SRcar}(g_n+2a)+2m_{Pcar}a-FR_{car}}{(P+BQ)(g_n-a)-m_{Pcwt}a+FR_{cwt}}. \tag{21}$$

For the empty car at the highest landing:

$$\frac{T_1}{T_2} = \frac{(P+BQ)(g_n+a)+2M_{SRcwt}(g_n+2a)+m_{Pcwt}a-FR_{cwt}}{(P+M_{Trav})(g_n-a)-2m_{Pcar}a+FR_{cwt}}. \tag{22}$$

These can be evaluated with the parameters in Table 1 for the conventionally guided situation. Here, since the suspension is coincident with the centres of gravity of the empty car and load (and assumed also for the counterweight), minimum values for FR_{car} and FR_{cwt} cannot be ensured as required in EN 81-50, 5.11.3 and so these are set at zero.

So for the full car at the lowest landing: $\frac{T_1}{T_2} = \frac{(1250+1000)(9.81+0.5)+2x25x(9.81+1)+2x30x0.5}{(1250+0.45x1000)(9.81-0.5)-30x0.5}$=1.50.

For the empty car at the highest landing: $\frac{T_1}{T_2} = \frac{(1250+450x1000)(9.81+0.5)+2x25x(9.81+1)+30x0.5}{(1250+12)(9.81-0.5)-2x30x0.5}$=1.54.

In this example, the influence of the pulleys is almost negligible and clearly the applied traction ratios are very much within the critical traction ratio calculated.

In the case of the cantilever guided configuration, the parameters used to calculate the applied traction ratios would be identical except that, if sliding guide shoes are used, it is reasonable to argue that, there will always be a frictional force on the car side. In this situation, the worst case is the lowest force so the value of FR_{car} should reflect the minimum steady load on a guide i.e. with empty car:

$$F_{min} = \frac{g_n(1250x500)}{2x2800}. \tag{23}$$

We can evaluate FR_{car} for this situation, taken on 4 guide shoes which have coefficient of sliding friction μ_g:

$$FR_{car} = 4\mu_g F_{min}. \tag{24}$$

Using a worst case (minimum value) for guide shoe coefficient friction of 0.05, this gives:

$$FR_{car} = 4x0.05x1095 = 219 \text{ N}$$

In calculating the likely friction force resisting the normal operation, say for the selection of a machine with sufficient torque, higher values should be used reflecting higher guide forces at full load and reflecting more realistic values of friction normally expected.

Re-evaluating (21) and (22) as above except with this value for FR_{car} leads to:

So for the full car at the lowest landing: $\frac{T_1}{T_2} = \frac{(1250+1000)(9.81+0.5)+2x25x(9.81+1)+2x30x0.5-219}{(1250+0.45x1000)(9.81-0.5)-30x0.5}$=1.49;

and empty car at the highest landing: $\frac{T_1}{T_2} = \frac{(1250+450x1000)(9.81+0.5)+2x25x(9.81+1)+30x0.5-219}{(1250+12)(9.81-0.5)-2x30x0.5}$=1.52.

Clearly all these values for applied traction ratios under emergency braking are comfortably within the critical traction ration calculated earlier. It can be observed that the use of friction forces of this size on a cantilever guided arrangement have not reduced the applied traction ratios significantly.

4.4 Further comment

In this example the applied traction ratios are determined largely by the main lift masses (although this may not be the case in other situations). In such cases, the use of simpler equations might be an alternative to the method in EN 81-50 (recalling that following these is not a normative requirement of EN 81-20). In place of the evaluation of all the various elements, some could be omitted and a suitable margin between applied and critical traction ratios used to take account of the neglected factors (and perhaps also to account for errors in the setting or measurement of parameters such as the empty car weight and counterweight balance). The equations in the Clause 9 notes of the previous EN 81-1: 1985 [6] can be seen to be such a simplification. Here there was a coefficient, C_2, introduced to cope with the wear of V grooves which has been superseded by the more detailed approach to calculating the critical traction ratio of these.

5. ROPE FACTOR OF SAFETY CALCULATIONS

EN 81-20 [1], 5.5.2.2 has requirements similar to those of EN 81-1 with a normative reference to clause 5.12 of EN 81-50. EN 81-50, 5.12 includes the calculation of an additional minimum factor of safety for ropes on traction lifts. This is generally as EN 81-1 Annex N with main changes being:

- Increased values for $N_{equiv(t)}$ for V grooves of 36° to 45°
- New value of $N_{equiv(t)}$ for V grooves of 50°
- The row for $N_{equiv(t)}$ previously for undercut-U and –V grooves is now for undercut-U.
- More definition on what is a reverse bend – rope distance between fixed pulleys less than 200x rope diameter and the bending planes are rotated through more than 120°.

5.1 Determining the number of equivalent pulleys

EN 81-50 Annex E has examples to assist with determining the number of equivalent pulleys, N_{equiv}. In this example, the worst case section of ropes will be where the traction sheave and two car pulleys run (there is no section of the ropes over which the traction sheave, car pulleys and counterweight pulley runs). Then the number of equivalent pulleys, N_{equiv}, is:

$$N_{equiv} = N_{equiv(t)} + N_{equiv(p)}. \tag{25}$$

The equivalent number of deflection pulleys, $N_{equiv(p)}$, considers the number of pulleys with simple bends N_{ps}, the number of pulleys with reversed bends N_{pr}, and the ratio between the traction sheave diameter, D_t, and the pulley diameter, D_p:

$$N_{equiv(p)} = \left(\frac{D_t}{D_p}\right)^4 \left(N_{ps} + 4N_{pr}\right). \tag{26}$$

Since there are no reversed bends and two simple bends (car pulleys) then we can evaluate this as:

$$N_{equiv(p)} = \left(\frac{320}{320}\right)^4 (2 + 4x0) = 2$$

The equivalent number of pulleys for the traction sheave, $N_{equiv(t)}$, is found from Table 2 in 5.12.2.1 of EN 81-50. In the example above, this is 5 for a hardened V groove of 50° angle and so $N_{equiv} = 7$.

5.2 Example minimum safety factor calculation

It is now possible to evaluate the minimum value of safety factor from EN 81-50, 5.12.3:

$$S_f = 10^{\left(2.6834 - \frac{log\left(\frac{695.85x10^6 N_{equiv}}{\left(\frac{D_t}{D_r}\right)^{8.567}}\right)}{log\left(77.09\left(\frac{D_t}{d_r}\right)^{-2.894}\right)}\right)}.$$ (27)

Using $D_t/D_r = 40$ and $N_{equiv} = 7$, the minimum required safety factor, S_f, can be evaluated to be 16.

If 8 mm ropes are selected of 43 kN minimum breaking load, then it is straightforward to determine that 5 ropes attain the necessary minimum safety factor with a safety factor of 19.

5.3 Influence of groove type and parameters, groove pressure

As a comparison, and to illustrate the potential impact of the changes to $N_{equiv(t)}$ for V grooves in Table 2 from those in EN 81-1, we can evaluate S_f for a V groove of 45° (where the value has changed the most) using the values of $N_{equiv(t)}$ from EN 81-1 (4.0) and from EN 81-20 (6.5). Then the minimum safety factor for EN 81-1 would be 15.5 and for EN 81-20 would be 17.6; a relatively modest improvement.

The calculation for S_f allows for the selection of ropes to meet the EN 81-20 standard which as noted earlier is a normative requirement of the standard. This method allows the selection of roping to take account of the nature of traction sheave grooves and pulleys reducing the lifetime of steel wire ropes. Further consideration of the pressure of the ropes in the traction sheave grooves is not a part of the safety standard but would usually be carried out as part of selecting and coordinating the wire rope and traction sheave hardness.

In this case, with hardened V grooves, the pressure in the grooves is of the order of 9.3 N/mm². While this would be high for conventional sheave materials, depending on the selection of sheave material and wire rope tensile strength, it could be considered acceptable.

As a comparison, if the groove were to be treated as an unhardened undercut U ($N_{equiv(t)} = 15.2$) then the minimum required safety factor would be 23. This would require at least one more rope and would therefore reduce the groove pressure accordingly.

It was noted above from the evaluation of critical traction ratios that unhardened V grooves with 105° undercut have similar calculated critical traction ratios as hardened 50° V grooves. So grooves of equivalent traction are not equivalent in terms of making rope factor of safety calculations. From an engineering perspective, selecting a hardened V groove, with the smaller $N_{equiv(t)}$, by setting a lower minimum factor of safety, allows fewer ropes than if an unhardened groove were selected.

6. RAMS, CYLINDERS, RIGID PIPES AND FITTINGS CALCULATIONS

EN 81-20 makes normative references to 5.13 of EN 81-50 for calculations for pressure and buckling of the jack, from 5.9.3.2, and for pressure of rigid pipes and fittings, from 5.9.3.3.2. EN 81-50 clause 5.13 is generally as EN 81-2 Annex K with the main changes being:
- Calculation for wall thickness in 5.13.1.1 now correctly uses the internal diameter (so wall thicknesses calculated to EN 81-2 would be slightly thicker).
- Errors corrected in 5.13.1.2.4 for flat bases with welded flange.
- Error corrected to buckling calculation of telescopic jack without guidance yoke.

On the basis that there are no significant changes to these calculations, they are not considered further here.

7. UNDERLYING ASSUMPTIONS – USUAL ENGINEERING PRACTICE

There are many assumptions made in the writing of a standard; in the case of EN 81-20, many are stated explicitly in clause 0.4. Included in the assumptions at 0.4.3 and at 0.4.12 are:

"Components are…designed in accordance with *usual engineering practice* and calculation codes taking into account all failure modes;" and that:

"a mechanical device built according to *good practice* and the requirements of the standard….will not deteriorate to a point of creating hazard without the possibility of detection provided that all of the instructions given by the manufacturer have been duly applied…".

Further guidance on the importance of assumptions and some of the concepts included in the assumptions is available in CEN/TR 81-12 [7]. Although the scope includes: "This Technical Report gives guidance to users, specifically outside Europe….", it is of more general interest. The technical report (it is not a standard and does not contain normative requirements) provides some helpful guidance on:

- the use of words such as "shall", "should", "may" and "can" in standards;

- guidance on notes and annexes including the difference between "informative" and "normative";

- more guidance on the assumptions and how these could be applied in different territories;

- references to EN standards; and

- specific national requirements.

In particular at 5.7, it discusses good engineering practice and elaborates important roles for the designer. Included in these is the use of calculations where CEN/TR 81-12 makes some important points in the context of the example calculations made above.

- For every calculation, all probable load cases need to be defined. It may be the case that a factor is not included in the equations and method in EN 81-50 and that additional factors need to be included. Clearly the designer should take account of these.

- When using calculation methods, consideration should be given to the inclusion of inherent simplifications and error factors. In the context of using simplified equations for calculation applied traction ratios, this would imply the use of a factor to take account of these simplifications such as was discussed in section 4.4.

The final point made is that good engineering practice entails subsequent design review by peer(s) or expert(s) in the appropriate discipline. This discussion in CEN/TR 81-12 therefore very neatly frames the context for the issues discussed in this paper.

8. CONCLUSION

The example calculations have been made using a set of lift parameters which are quite unremarkable. For this example design, car guide calculations were made for both conventionally guided and cantilever guided configurations, critical and applied traction ratios and rope minimum safety factor. These helped to highlight some changes between the approaches taken in EN 81-1 and EN 81-50.

For guide rail calculations, EN 81-20 has a normative requirement to evaluate the vertical loads on guide rails and a new requirement to consider deflection of building structure. For the calculations in EN 81-50, which are one method to satisfy the normative requirements of EN 81-20, the most significant change is the inclusion of the deflection in the building structure and guide brackets into the deflection calculations.

Example calculations illustrated some important differences between conventionally guided and cantilever guided configurations. The worst case selected was for safety gear operation showed both stress levels approaching the permitted stress level and deflections close to or greater the permitted levels.

The engineering implications of reducing guide rail deflections was considered where it was noted that reducing the distance between fixings is very much more effective in reducing deflections than either increasing guide rail size or reducing loads on the guides.

For traction calculations in EN 81-50, which were seen to be referenced informatively from EN 81-20, the calculation of critical traction ratios was unchanged from the EN 81-1. Two groove parameters were selected reflecting similar critical tractions ratios.

The emergency braking situation was calculated. On the simple lift model considered, the influence of omitting or including elements such as pulley masses and guide rail friction was considered. The conclusion was that simplified calculation methods might be used on simplified designs if these included a suitable factor or margin to take account of the parameters neglected or not included.

For the minimum safety factor for ropes on traction lifts in EN 81-50, which is normatively referenced from EN 81-20, the model lift allowed a simplified evaluation of the number of equivalent pulleys and a calculation of the minimum safety factor. This was calculated for both groove profiles to illustrate significant differences in these for different groove profiles of equivalent traction.

Calculations were also made to illustrate the relatively modest influence on safety factor from the changes in the table for V grooves from EN 81-1 to EN 81-50.

The discussion closed with a brief review of some useful guidance in CEN/TR 81-12 on good engineering practice and, to close the loop, on some guidance on making calculations to support the design.

Closing remarks: the calculations presented necessarily are not comprehensive or exhaustive. Where calculations are being made to demonstrate conformity with EN 81-20 then these should be comprehensive i.e. all cases calculated and all relevant factors taken in consideration.

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BIOGRAPHICAL DETAILS

Nick Mellor has worked for the UK's Lift and Escalator Industry Association (LEIA) as Technical Director since January 2012 and has been in the industry for 22 years. Nick was in the inaugural cohort of the MSc in Lift Engineering at Northampton. More recently, as an Associate Lecturer, he has done some tutoring on the MSc. The idea for this paper came from a chance remark from the technical manager of a UK lift company earlier this year. Hopefully the paper is of some interest to both those in the industry working with EN 81-50 and those studying lift engineering.

Lift Systems in High-Rise Buildings: Handling Capacity and Energy Efficiency

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Abstract As more people have to live and work with limited available area, buildings are getting taller. Designers should provide sufficient handling capacity and acceptable quality of service should also consider energy. This paper compares the energy consumption of a system with two independent running cars in one shaft versus a double decker system in a local group.

1   INTRODUCTION

More and more people have to live and work with limited available area. Buildings are getting taller to concentrate these requirements in as little space as possible. These buildings have to be made accessible all the way to the top. Enough transport capacity for people and material flow have to be provided to enable optimal use of buildings. The waiting times and time to destination of the transport facilities should be as short as possible.

A good lift concept with sufficient handling capacity and acceptable quality of service should also consider energy. VDI 4707 [1] does not necessarily lead to the system or system combination, which provides the lowest energy consumption with the best quality of transportation service.

The use of the right lift system and controller types for the specific requirement is essential. In general a modern simulation program should be used. Traditional calculation or estimation methods using round trip time and interval calculations can lead to too many or too big lift cars; lift speeds often become too high. "Over-dimensioning" leads to high lift costs as the structural and electrical loads, together with the physical equipment dimensions have to be accommodated. This leads to increased costs and reduces the chance of an economical design for the building. Also energy costs of the building in use will increase.

2   PLANNING WITH DIRECT CONNECTION TO THE DESTINATION FLOOR

Most lift users prefer to reach their destination floor directly, without any transfer. With conventional lift systems, the planner will reach limits very quickly as building height increases.
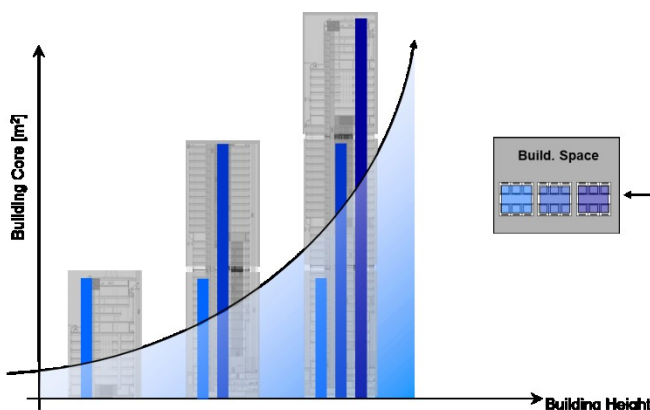
Figure 1: Building space requirements with low-mid- and high rise lift group (direct connection to destination floor)

As building height increases, the number of shafts required becomes too high (see Figure 1), the volume of the building core becomes too big and the available area for economical usage is dramatically reduced.

3   PLANNING WITH TRANSFER FLOORS

Planning with transfer floors [2] in the upper part of the building allows stacking of lift shafts in local areas. The shaft arrangement can be more economically as there are less shafts going through the whole building. The transfer floor (sky lobby) is served by shuttle lifts from the ground floor. These lifts can work at high speeds and provide a high handling capacity due to less or preferable no intermediate stops. With this arrangement fewer lifts will go down to the main lobby (Figure 2).
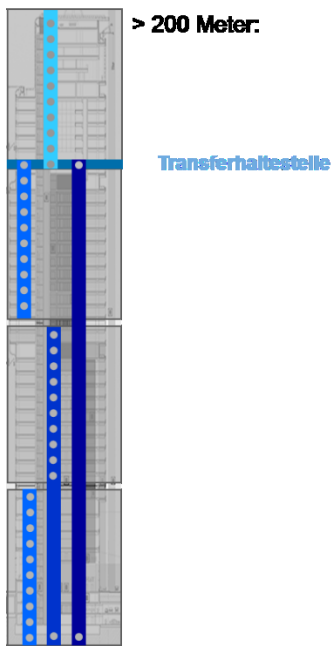
Figure 2: Lift arrangement with stacked shafts and shuttles

4   PLANNING WITH DOUBLE DECKER

Double Decker lifts can reduce the numbers of lift shafts needed [3]. A two-level-lobby is required to allow loading of upper and lower cars at the same time.

With Double Decker lifts the traffic flow in the entrance area has to be coordinated. Passengers who want to reach an even numbered floor must enter in the upper car via the upper lobby. Passengers who want to reach an odd numbered floor must enter to the lower car via the lower lobby.

By serving two floors at the same time during up peak traffic the number of stops during an average round trip is reduced. This results in less times losses.

Double Decker lifts in local groups should be used with destination control systems. The disadvantages of the Double Decker lifts are the big masses and big inertias. Car weights of more than 11000 kg (see Figure 3) and counterweight masses of 13500 kg can be reached easily (e.g. for capacity of two x 1600kg). Additionally there are big inertias associated with the machine, diverter pulleys and compensation ropes. Also the ropes themselves will have big masses when steel ropes are used. All these masses have to be accelerated and decelerated, even when only a few passengers are using the car. This causes high acceleration currents and high energy consumption.

The advantage of the Double Decker can be seen when even and odd floors are served at the same time. The available handling capacity is almost double compared to single deck lifts during peak traffic.

This disadvantage arises, when during peak-traffic and off-peak-traffic, calls from odd to even floors need to be served. Two connected cars have to be moved, even if only one of the cars can be used.

Passengers are also irritated when in-car-waiting-time occurs due to other deck loading / unloading.

Using conventional Double Decker lifts, architects have to plan the same floor to floor distances, which allows them less flexibility in their building. Flexible Double Decker lifts, which allow a limited adjustment for floor levels with different interfloor distances, require additional mechanical devices, which results in more masses to be moved.

Nevertheless we see the optimal usage of the Double Decker lift as a shuttle. Only the main lobby and sky-lobby have to be planned with the same floor to floor distance; all intermediate floors are not be served, so can be planned without fixed floor heights.

Using Double Decker as shuttles, the trips are always long distance. There are fewer stops which reduces the overall energy consumption.
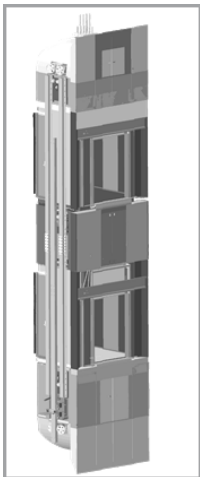
Figure 3: Double Decker Car with non-adjustable floor to floor distance
→ 9500kg – 12500kg (empty car weight, dependent on capacity)

5   PLANNING WITH TWO INDEPENDENT CARS RUNNING IN ONE SHAFT

With a system that runs two cars independently within one shaft [4], the number of lift shafts can also be reduced. Planning with a two-level-lobby gives the best performance, allowing the upper and lower cars to be loaded and unloaded at the same time.

The upper lobby is the entrance level to an upper zone within the lift group; the lower lobby is the entrance level to a lower zone within the lift group. Ideally zone are set so that upper and lower cars will have to serve the same number of people or floors, e.g. lower zone: floor 3 to 9; upper zone: floor 10 to 16.

During off-peak traffic the lifts can run without limitation, serving calls in both zones.

The flexibility of having two independent cars in a shaft is particularly evident during interfloor traffic. In buildings where tenants use multiple floors, more cars can be used for interfloor traffic

compared to a Double Decker system. This is because the independent car system does not always require two cars to serve two adjacent levels at the same time.

 The controller decides which destination call gets the highest or lowest priority to provide the best performance to the main traffic flow.

The inertias and masses of cars are the same as conventional lifts (single cars). To save energy, only the cars needed to provide the required quality of service are moved.
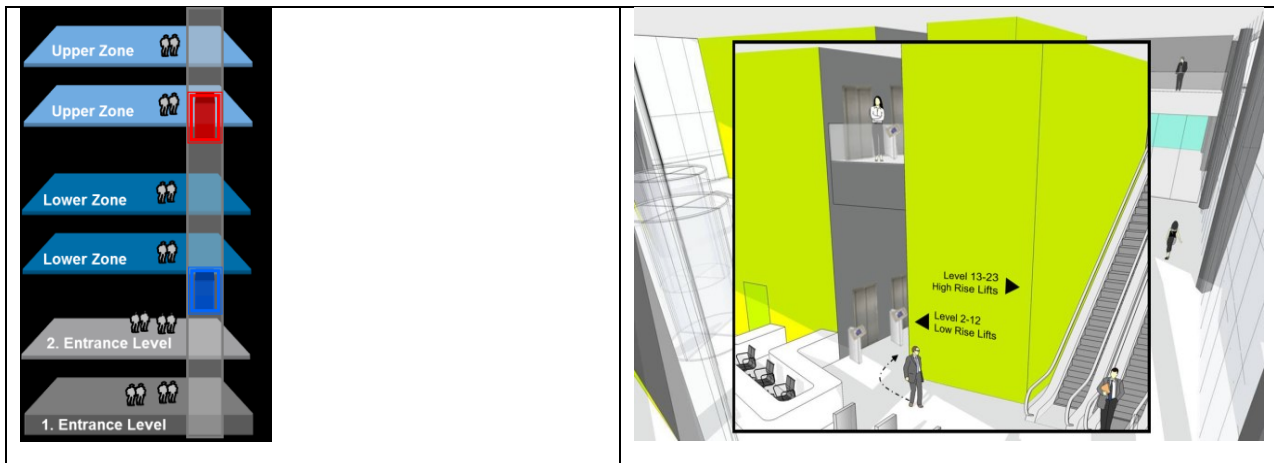
Figure 4: Two independent cars in one shaft with zoned arrangement

6   COMPARISON OF ELECTRICAL LOADS USING A SYSTEM WITH TWO INDEPENDENT RUNNING CARS IN ONE SHAFT VERSUS A DOUBLE DECKER SYSTEM IN A LOCAL GROUP

When comparing two lift groups with similar handling capacity and comparable quality of service, the electrical loads of Double Decker solution is nearly the double that of an installation with independent running cars. To demonstrate this, the results presented in Figure 5 were generated with the application an all-day office traffic template [5] in an industry standard simulation model [6] for a 100m project. The simulation software has been extended to include a sophisticated energy model [7]. The Double Decker solution requires much bigger electrical equipment, e.g. transformer, electrical cables, generators.

The energy consumption is approximately 20-30% higher for the Double Decker groups. Even if both lift systems can be provided with the same energy efficient class according to VDI 4707, the difference in energy consumption is huge. This is illustrated by the simulation results in Figure 6. Figure 7 helps understand the results by comparing the power consumption of a single trip for a double and single deck lift using a single trip model in Matlab [8]. The difference in energy consumption between the two systems is not highlighted by VDI 4707 as it does not consider the behavior of systems during daily usage. The Double Decker moves more cars during off-peak-traffic, which is most if the day.   Therefore for best performance, and least wastage of resources, it is necessary to plan each system according the actual building usage.
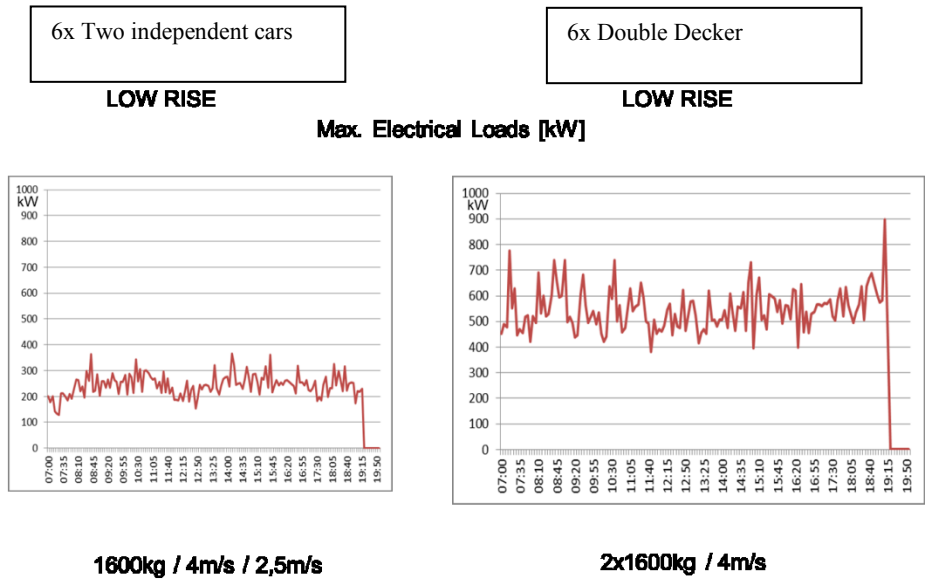
Figure 5: Electrical peak loads, 6 shafts with two independent cars vs. 6 Double Deckers
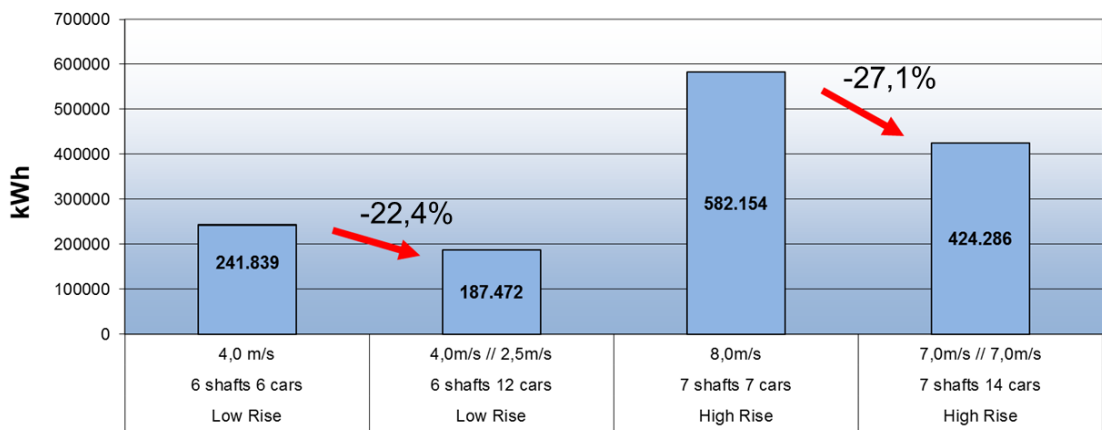
Figure 6: Comparisons of energy consumption system, two independent cars versus Double Decker lifts with same traffic demand and similar quality of service. Both systems have the same "Energy Efficiency Class" according to VDI 4707.
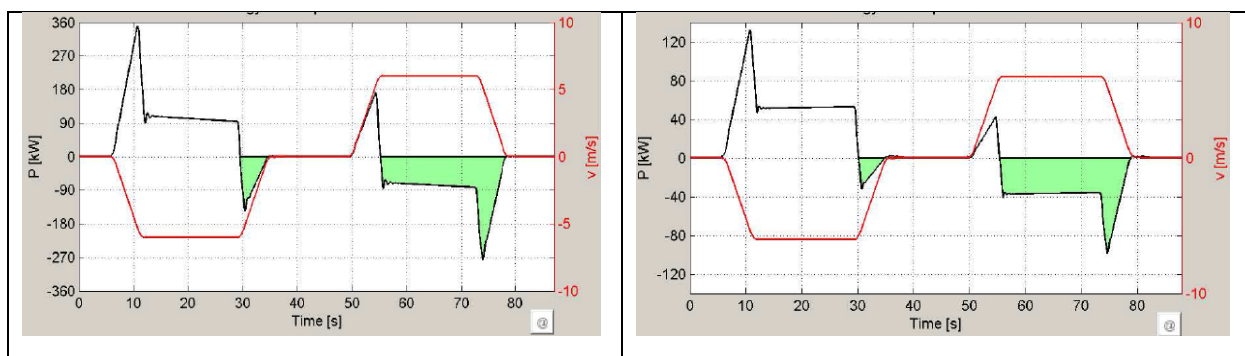
Figure 7: Double Decker power consumption (left diagram) / one independent car power consumption (right diagram) for VDI reference trip

7   CONCLUSIONS

The combination of Double Decker shuttle lifts and two independent cars running in shafts for local groups provides a space saving, and energy efficient solution for high rise buildings.

With this approach to planning, the building can obtain an economical shaft arrangement, offer the maximized usable area and still provide good handling capacity and quality of service.

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BIOGRAPHICAL DETAILS

Joerg Mueller studied Electrical Engineering and joined ThyssenKrupp Aufzugswerke in 1993. He worked in the testing division of R&D, managed the modernization department. |Since 2005 Joerg has been working as Senior Engineer and Head of Major Project Consulting for the factory in Germany. He supports Major Projects for New Installation and Modernization. He has developed together with his team new concepts for vertical transportation in high-rise buildings, considering space efficient planning, quality of service of lift systems and energy consumption; using modern simulation methods.

Comparing the Energy Consumption of Elevators with Different Drive Technologies

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Keywords: energy efficiency, lift, drive technology, machine, Ward-Leonard, Modernization.

Abstract. In the last decades the drive and machine technology has made a big step forward also in regards of energy efficiency. This also improves the energy efficiency of lifts, significantly, which strive towards the ultimate and unattainable goal as a perpetual motion machine. While lifting loads and persons, electrical energy is converted into potential/kinetic energy and reconverted later. Measurements which compare different drive technologies are usually conducted at different lifts, where also the mechanical system varies. An increase or decrease in energy consumption may be caused by the mechanical system and not by the drive. This paper introduces measurements of different drive technologies used in the last decades and compares lifts, where also the mechanical part is the same. Furthermore, these lifts are simulated with state of the art drive technologies. The energy saving potential is identified and the different drive technologies are being compared.

1   INTRODUCTION

New installations of lifts are usually equipped with PSM[1] machines, today. This is due to the high energy efficiency, low noise in comparison to geared machines, and shaft efficiency in the MRL[2] market. In the modernization market there is still a high amount of lift installations which are equipped with voltage controlled inverters and machines with gear boxes or Ward-Leonard drives.

A lot of these lifts will be modernized within the next years. The main challenge is to find a cost optimized and sustainable solution which fits best into the market segment. In particular, if only a part of the lift e.g. the drive system is modernized while the mechanical system persists this could be a sustainable solution. However, there are many possibilities to modernize a lift, starting with the replacement of single components to a full replacement. This leads to many different configurations and thus it is economically impossible to install and measure all this variants. Therefore in [1] a simulation environment has been introduced and validated at a real lift, but detailed information about the parameters is required. Usually this information is not on hand for old drive technologies and thus this paper compares different drive setups at a lift where energy consumption has been measured before and after the modernization. These measurements are extended by simulations to evaluate also further variants.

A closer look at the modernization market of rope lifts, especially with a look at the replacement of the drive system, leads to the question: Which components of the drive system should be replaced to find an economical and energy efficient solution?

In case of a full replacement of the total lift (comparable to a new installation) either a PSM with non-regenerative or a PSM with regenerative drive should be used. It is proposed to use a regenerative drive system even in the low rise market segment [3].

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[1] PSM: Permanent Magnet Synchronous Machine
[2] MRL: machine roomless lift

In case of a partial modernization for low-rise lifts also the combination of state-of-the-art geared machine with regenerative inverter shows interesting economical and high energy saving benefits, which has been shown in [2].

This paper focus on mid-rise lifts, where often Ward-Leonard drives has been used in the past. In particular, the energy savings are proven by comparable measurements. In the following chapters existing drive technologies are briefly described and measurements and simulations are performed to evaluate the energy savings of different configurations.

2 OVERVIEW OF DIFFERENT DRIVE SYSTEMS

The considerations in this paper are based on rope lifts, hydraulic lifts have not been considered. In rope lifts the cabin and counterweight is usually balanced with around 40-50% of the rated payload, which is today's standard.

Figure 1 shows the simulated energy consumption, to get a general idea about the differences between a low-rise (left) and high-rise (right) elevator. On the left axis the active power and on the right axis the speed is given over the time. Additionally, the regenerative part of the energy is marked by the green area. The high inertia of the high-rise elevator leads to a high acceleration and deceleration peak power in comparison to the nominal travel and therefore the overall system inertia has a big influence on the energy consumption and calculation.

For the simulation results in chapter 4 it is necessary to use an accurate model to obtain appropriate results, which has been discussed in [1]. Especially the use of characteristic maps for the efficiency during acceleration and deceleration is important while the use of formulas with constant efficiencies leads to high deviations [1].

For the low-rise elevator in figure 1 the down travel with empty cabin consumes around 18.4 Wh, The travel in upward direction recovers -5.7 Wh into the grid. Thus around 31% of the energy is recovered, which also considers the non-recoverable part of idle consumption of controller and light. For the high-rise elevator even 62 % of the energy is regenerated, which results from a higher efficiency of the machine, as well as a low idle consumption in comparison of the energy consumed by the drive.
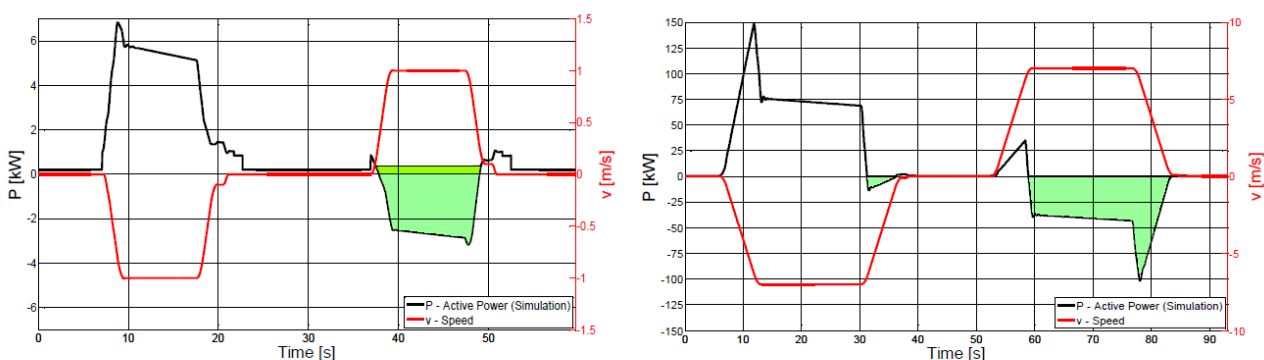
Figure 1 Comparison of Energy Consumption of a Low- and High-Rise Elevator

A closer look in the modernization market leads to different types of drive systems which have been used over the years. The most common systems are:

- Two speed machine
- Ward-Leonard drive (Motor generator)

- Phase-fired controllers (ACVV[3] drives)
- DC machine with thyristor controller
- Geared machine with VVVF[4] controller based on IGBT[5]
- Gearless machine with VVVF controller based on IGBT (mostly in combination with PSM)

Usually, an inverter with regenerative drive unit has the highest power factor as the wave form of the regenerated current is controlled. Looking at the history, the Ward-Leonard drive has been installed until 1970. The major part of installations has been modernized so far mostly by static inverters where the DC machine has been kept in the installation (this was practice until 1980) [4]. Starting in 1990s the gearless drives with IGBT controller has been widely used and is the most common drive system, nowadays.

3   MEASUREMENTS

In this chapter a Ward-Leonard drive system is compared with a gearless induction machine driven by either a regenerative or non-regenerative inverter. Already, in 1995 first energy measurements have been conducted at a modernization site in Stuttgart, Germany. A Ward-Leonard drive has been replaced by a gearless induction machine including an IGBT inverter. The shaft equipment and car have been kept in the installation, while the controller and drive system were changed. The main parameters of the lift configuration are shown in table 1.

Table 1 lift configuration

Type of drive system:	Ward-Leonard	Gearless machine "DA330" with inverter "API60R"
Lift data	Q = 1,200 kg Vn = 2.5 m/s; Roping = 2:1 Total travel height = 52 m with 13 stops Car and counterweight with roller guides	
Type of motor	DC motor (HGF 2682-4)	Induction motor (DAF330 M002)
Traction sheave	600 mm	440 mm

The configuration of the drive system before and after the modernization is shown in Figure 2. The left figure shows the Ward-Leonard drive which was originally used, where the lift's motor was a DC machine. Due to the three stages of energy conversion the overall efficiency is very low. In the right figure the modernized drive system is shown, where the inverter is controlled by power electronics (PE) driving an induction motor.

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[3] ACVV: Alternate Current Variable Voltage
[4] VVVF: Variable Voltage Variable Frequency
[5] IGBT: Insulated Gate Bipolar Transistor
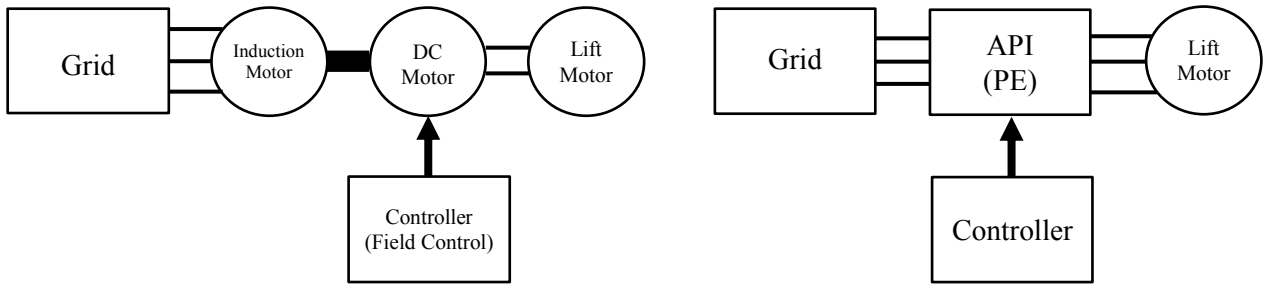
Figure 2 Ward-Leonard Drive in Comparison to a Gearless Drive with IGBT Technology

A travel of the Ward-Leonard drive with no payload is shown in Figure 3. It is a travel between the floors 10 and 13 in down and up direction. The red curve shows the speed (right axis). The black curve shows the active power. Even if the lift is stopped the Ward-Leonard drive system "wastes" – in this configuration – about 10 kW. For acceleration a peak power of almost 70 kW is needed. In addition, the reactive power is higher than 20 kVar which leads to a worse power factor. From the figure it is also visible, that the Ward-Leonard drive is able to recover energy which is shown in green. However, due to the low efficiency only little energy is recovered.
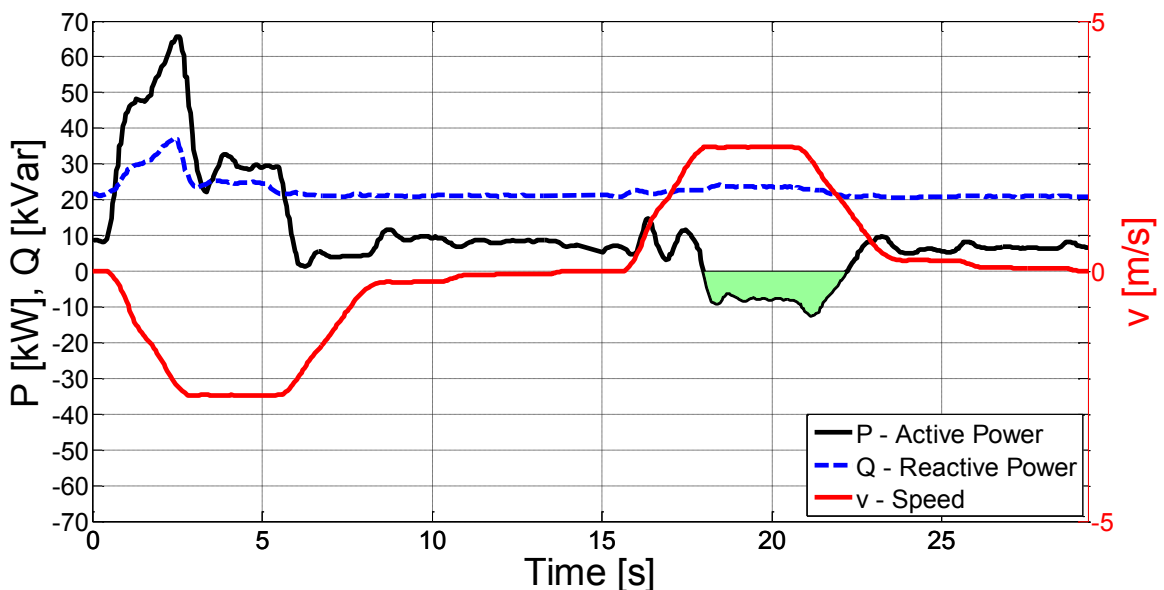
Figure 3 DC Machine with Ward-Leonard Drive System

Now, the results are compared with the induction motor driven by the IGBT inverter "API60" which is shown in Figure 4. The active peak power for accelerating the lift is reduced to 40 kW that is about 43 % of reduction. The up travel with no load recovers no energy, as the first measurements have been made with a non-regenerative drive system.
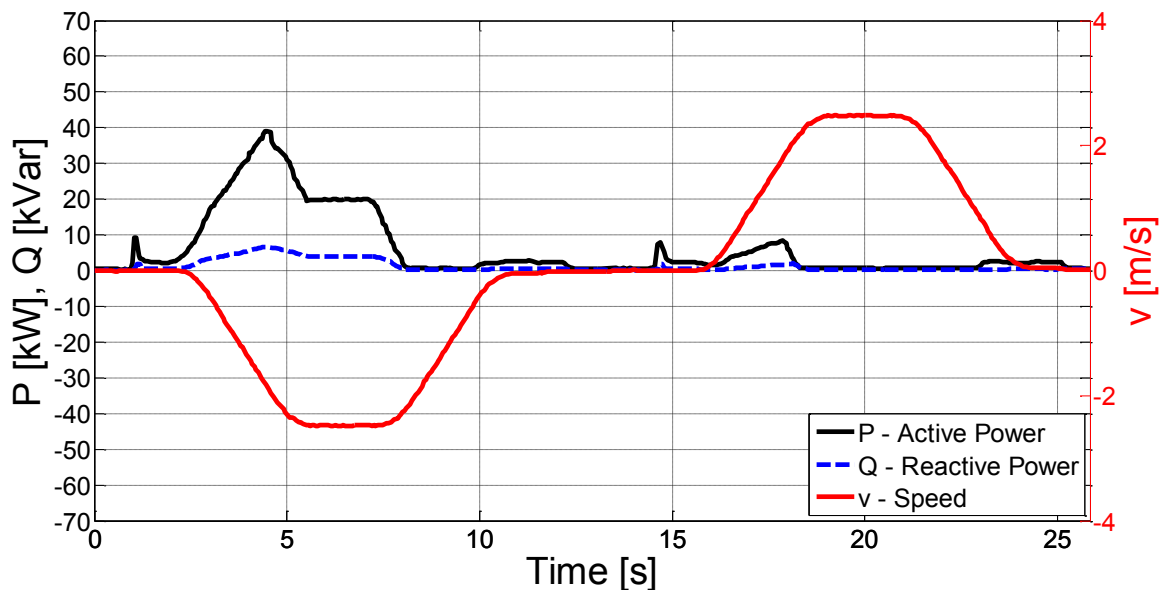
Figure 4 Compact Gearless with non-regenerative API Drive

Figure 5 shows the same drive configuration as in Figure 4, but the inverter "API60-R" with energy regeneration has been used. The regenerated part is shown in green.
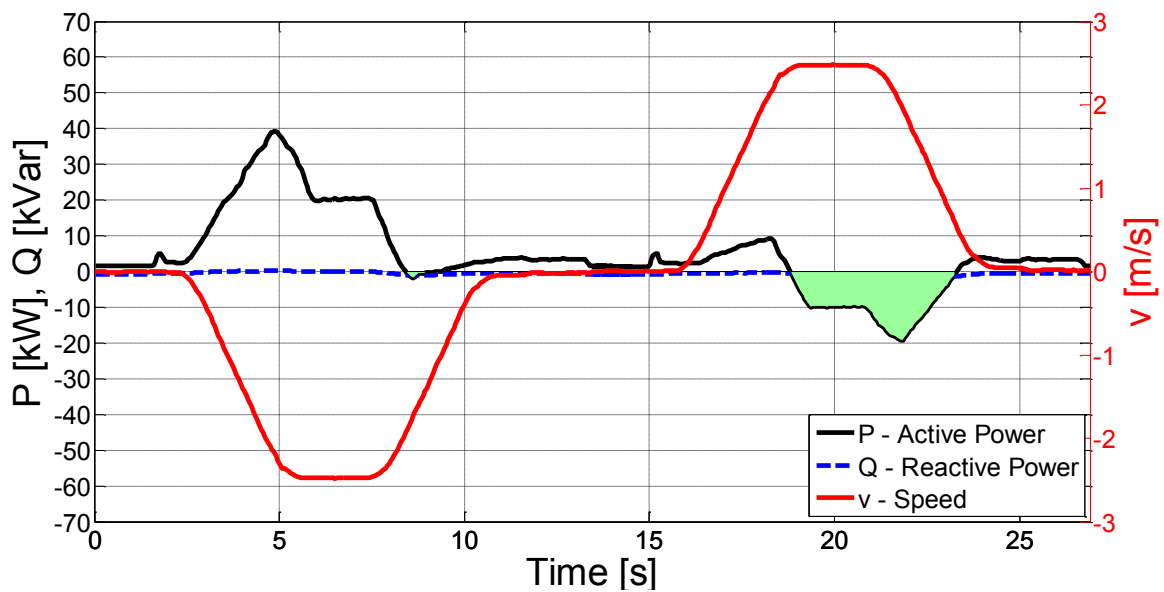
Figure 5 Compact Gearless with API regenerative Drive

Looking at the total energy consumption a comparison has been performed based on the travel cycle about 104 m stopping at the following landings: 13-2-1-2-13. The specific demand of the Ward-Leonard drive system has been measured with 2.04 Wh/m. For this cycle, even the induction machine without energy recovery consumes 36 % less. Furthermore, if compared with the regenerative drive the energy consumption is even lower and 53% less. This difference resulting mainly as for the Ward-Leonard drive system the energy is converted three times between mechanical motion and electrical energy. Also, the high masses of the machine rotors contribute to the higher energy consumption. Additionally, the strongly reduced peak power and increased power factor of the inverter drive which becomes more and more important for stabilizing today's grid.

Table 2 shows a summary overview of the energy consumption per year and connecting power. The energy consumption per year of the Ward-Leonard drive has been measured over 1.5 months and was then extrapolated for the whole year. The lift performed around 1170 runs per day while having 4.8 hours running time. Furthermore the annual demand of the induction machine with inverter is estimated based on the above mentioned driving cycle.

Table 2 Energy demand of different drive systems

	Ward-Leonard	Induction machine Non-regenerative	Induction machine Regenerative
Mains connection [kW]	33.0	19.2	19.2
Energy per year [kWh]	18,535	9,996	8,442

4   SIMULATIONS

The measurements of the chapter above are now compared with a simulation of the same configuration but application of state-of-the-art technology. Therefore a PSM, a VVVF inverter with regenerative drive unit and an up-to-date mechanical design is used. The lift's parameters are given in table 3.

Table 3 Parameter of the simulated lift

m_K [kg]	1200	Mass of empty cabin
m_G [kg]	2386	Mass of counterweight
m_{ZL} [kg]	1677	Maximum Payload
H [m]	52	Travel Height
J_m [kg m²]	3,6	Inertia of traction sheave
r_T [m]	0,22	Radius of traction sheave
$AufH$	2:1	Roping
ρ_{Seil} [kg/m]	2,8	Specific mass of all ropes
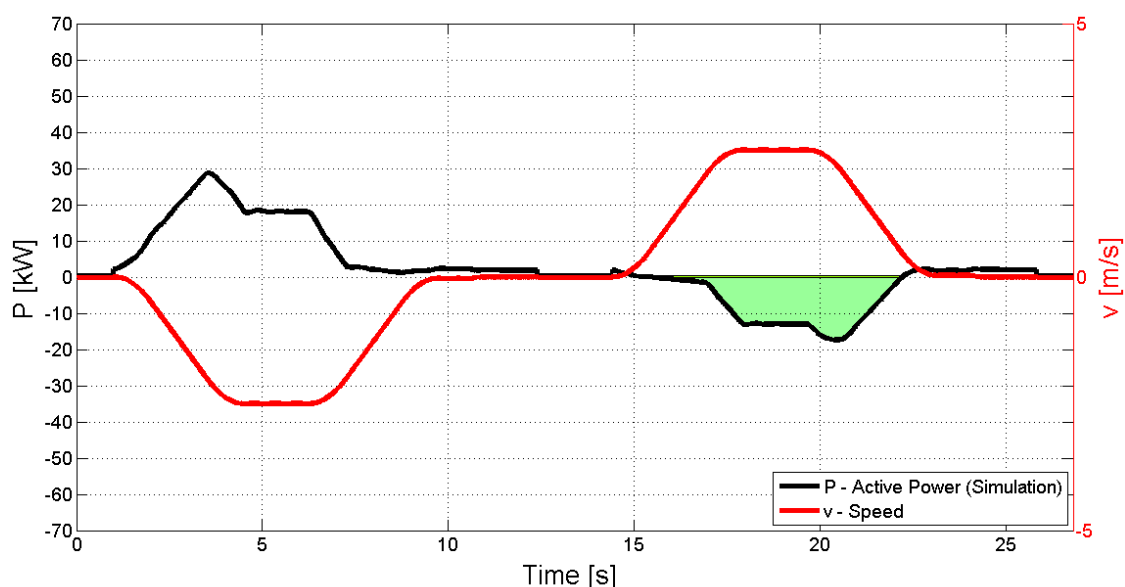
Figure 6 PSM machine with regenerative drive

Figure 6 displays the results of the simulation. Comparing the energy consumption of the lift containing the PSM drive the energy savings in regards to the Ward-Leonard drive are again significantly decreased to around 80 % during the travel cycle between floor 10 and 13. In addition, the peak power is further reduced by 10 kW. Looking at the whole travel cycle, around 47 % can be recovered during the travel in up direction.

Especially the higher efficiency of the PSM leads to smaller losses, resulting in reduced power consumption during the downward travel with empty car, as well as to higher energy recovery during the upward travel. Thus, a high energy efficiency of the drive doubles the energy benefits. Also the inverter has a higher efficiency due to transistors with fewer losses, resulting from advances in the semiconductor industry since 1995.

5   CONCLUSION

With introduction of the VDI 4707 in 2009 and the ISO 25745 which will be introduced soon the overall energy consumption of a lift becomes more and more important for new installations.

Even in the modernization market these figures can be used to make a modernization of a lift more attractive to the customer due to the high potential of energy savings.

The overall energy consumption of a Ward-Leonard drive in comparison to state-of-the-art technology results in up to 80 % energy savings if replaced by a PSM drive system. Even in old fashioned IGBT technology with induction machines further significant energy savings potential exists and a modernization become attractive to the customer.

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BIOGRAPHICAL DETAILS

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Modelling and Simulation of a Nonstationary High-Rise Elevator System to Predict the Dynamic Interactions Between Its Components

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Abstract. Lateral vibrations of the suspension and compensating ropes in a high-rise elevator system are induced by the building motions. When the elevator is in motion the length of the ropes change so that the natural frequencies vary, rendering the system nonstationary. In this scenario large displacements of the ropes occur when a passage through resonance takes place. Due to the nonlinear coupling, interactions between the in-plane and out of plane motions of the ropes occur. Furthermore, the car, counterweight and compensating sheave suffer from vertical vibrations due to the coupling with lateral vibrations of the ropes. This paper presents a mathematical model of a high-rise elevator system which can be used to predict the dynamic interactions taking place during its operation. The model is implemented in a high performance computational environment and the dynamic response of the system when the building is subjected to a low frequency sway, is determined through numerical simulation with the car following the kinematic profile dictated by the drive control algorithm. A case study is used to demonstrate resonance phenomena taking place during the operation of the system. The results predict a range of nonlinear dynamic interactions between the components of the elevator system, during travel and when the system is stationary.

1   INTRODUCTION

When one of the fundamental frequencies of the building structure coincides with the natural frequencies of the ropes in the elevator installation, large resonance whirling motions of the suspension and compensating ropes occur [1]. This results in impact loads taking place in the elevator shaft, leading to adverse dynamic behavior of the elevator system. When the elevator system is in motion transient/nonstationary resonance phenomena may take place. A nonstationary linear planar model of an elevator system was presented in [2] which was developed further in [3] to accommodate nonlinear modal interactions in a system consisting of a vertical rope of varying length moving at speed within a tall host structure subjected to a low frequency sway. The study presented in [4] involved the prediction of internal resonance behavior of an elevator system represented by a rope of time varying length translating vertically with a car modeled as a spring-mass system. In this paper a nonstationary model of a high-rise elevator system is developed. The system operates in a building host structure subjected to a low frequency sway. This model is then implemented in a high-performance computational platform to carry out numerical simulations in order to predict the dynamic interations between the building sway, the rope motions and the

vibrations of the elevator components such as the car, compensating sheave, and counterweight. The effects of centrifugal forces and coriolis acceleration arising due to transportation motion are accounted for.

2   DESCRIPTION OF THE MODEL OF AN ELEVATOR SYSTEM

The model of an elevator system with a car of mass M_1, compensating sheave of mass M_2, and counterweight of mass M_3, is depicted in Fig. 1. The suspension and compensating ropes have mass per unit length m_1 and m_2, elastic modulus E_1 and E_2, and effective cross-section are A_1 and A_2, respectively. The parameter b_1 represents the distance measured from the bottom landing level to the center of the compensating sheave. The parameter b_2 denotes the distance measured from the center of the traction sheave to the center of the diverter pulley and h_0 represents the distance measured from the bottom landing level to the center of the traction sheave. The parameter h_{trav} is the height of travel of the elevator car. The parameter h_{car} is the height of the car. The parameter h_{cw} is the height of the counterweight. The parameter h_t is the position of the elevator car measured from the bottom landing level to the bottom of the elevator car vary with time according to the kinematic profile dictated by the drive control algorithm.

The lengths of the suspension rope and of the compensating rope are defined as follows. The length of the suspension rope at the car side measured from the center of the traction sheave to the the termination at the car crosshead beam is denoted by $L_1(t)$. The length of the compensating rope at the car side measured from the termination at the car bottom to the center of the compensating sheave is denoted as $L_2(t)$. The length of the compensating rope at the counterweight side measured from the termination at the counterweight to the center of the compensating sheave is denoted by $L_3(t)$. The length of the suspension rope at the counterweight side measured from the center of the diverter pulley to the termination at the counterweight end is denoted by $L_4(t)$. The mass moment of inertia of the diverter pulley and the short stretch of the suspension rope between the pulley and the traction sheave is neglected in the simulation model. They vary with time according to the kinematic profile dictated by the dive control algorithm.

The response of the elevator ropes subjected to dynamic loading due to the building sway are represented by the lateral in-plane and the lateral out of plane displacements denoted as $V_i(x_i(t),t)$ and $W_i(x_i(t),t)$ where the subscripts $i=1,2,3,4$ correspond to the rope sections of length L_1, L_2, L_3, and L_4, respectively. The lateral in-plane and lateral out of plane motions of the ropes are coupled with their longitudinal motions that are denoted as $U_i(x_i(t),t)$. The longitudinal motions of the car, compensating sheave and counterweight are denoted as $U_{CR}(t)$, $U_{CS}(t)$, and $U_{CW}(t)$, respectively.

3 VIBRATION MODEL
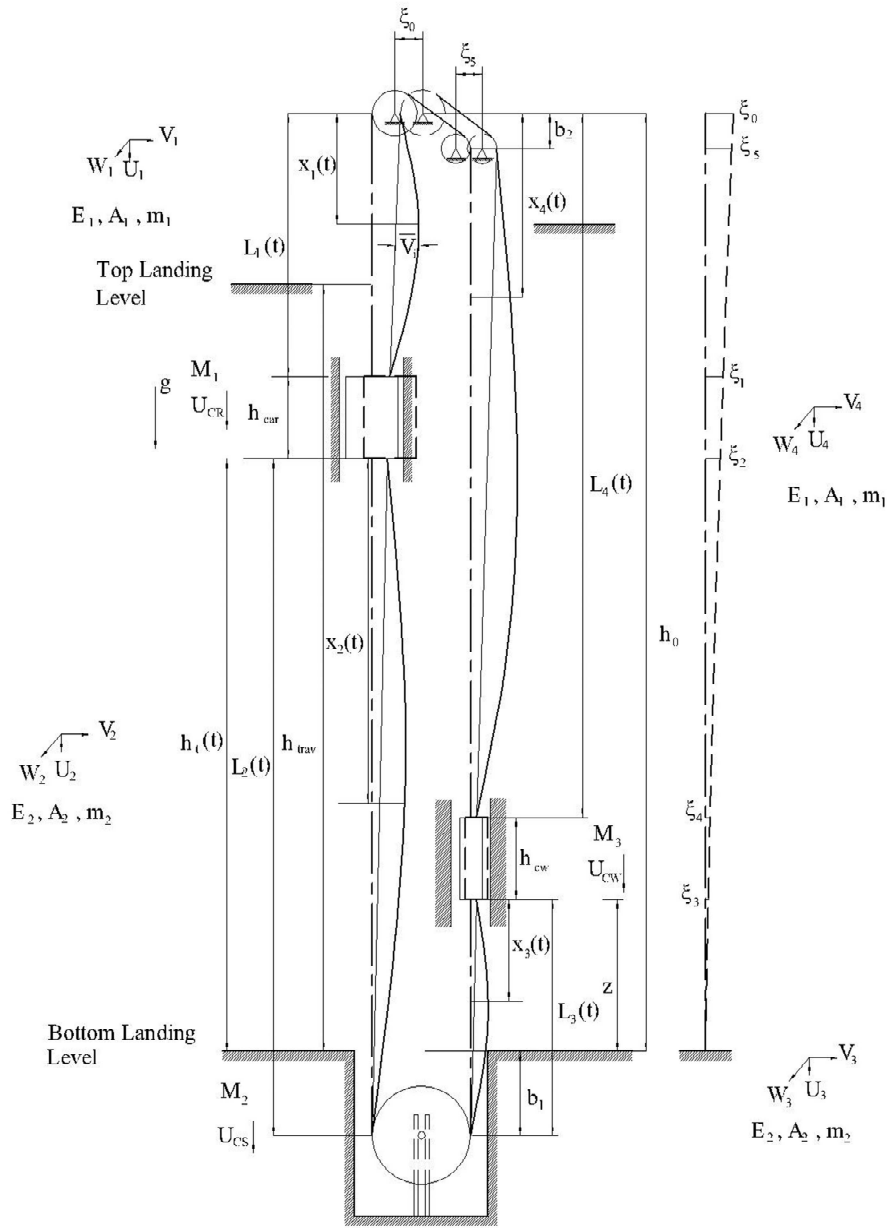
Figure 1 Elevator system

The axial Green's strain measure representing stretching of the rope section *i* is given as

$$\varepsilon_i = U_{ix} + \frac{1}{2}\left(V_{ix}^{\,2} + W_{ix}^{\,2}\right).$$ (1)

where $( )_x \equiv \dfrac{\partial( )}{\partial x}$. The equations governing the undamped dynamic displacements $U_i(x_i(t),t)$, $V_i(x_i(t),t)$, $W_i(x_i(t),t)$, $U_{CR}(x_{CR},\,t)$, $U_{CS}(t)$, and $U_{CW}(x_{CW},\,t)$ can be developed by applying Hamilton's principle, which yields

$$m_i V_{itt} + 2m_i v V_{xt} + m_i v^2 V_{xx} + ma_c V_{ix} - T_{ix} V_{ix} - E_j A_j \varepsilon_{ix} V_{ix} - T_i V_{ixx} - E_j A_j \varepsilon_i V_{ixx} = 0.$$ (2)

$$m_i W_{itt} + 2m_i v W_{xt} + m_i v^2 W_{xx} + m a_c W_{ix} - T_{ix} W_{ix} - E_j A_j \varepsilon_{ix} W_{ix} - T_i W_{ixx} - E_j A_j \varepsilon_i W_{ixx} = 0. \tag{3}$$

$$m_i U_{itt} - E_j A_j \varepsilon_{ix} = 0. \tag{4}$$

$$M_1 \ddot{U}_{CR} + M_1 a_c - M_1 g + T_1 (L_1) + E_1 A_1 (\varepsilon_1)\big|_{x=L_1} - T_2 (0) - E_2 A_2 (\varepsilon_2)\big|_{x=0} = 0. \tag{5}$$

$$M_2 \ddot{U}_{CS} - M_2 g + T_2 (L_2) + E_2 A_2 (\varepsilon_2)\big|_{x=L_2} + T_3 (L_3) + E_2 A_2 (\varepsilon_3)\big|_{x=L_3} = 0. \tag{6}$$

$$M_3 \ddot{U}_{CW} + M_3 a_{cw} - M_3 g + T_4 (L_4) + E_4 A_4 (\varepsilon_4)\big|_{x=L_4} - T_3 (0) - E_2 A_2 (\varepsilon_3)\big|_{x=0} = 0. \tag{7}$$

where T_{ix} represent the mean tension of each stretch of rope, g is the acceleration of gravity, a_c is the acceleration of the car, a_{cw} is the acceleration of the counterweight, $x_i(t)$ represent the spatial coordinate corresponding to the sections of the ropes of length $L_1(t)$, $L_2(t)$, $L_3(t)$, and $L_4(t)$ in time t, respectively and $( )_t \equiv \dfrac{\partial ( )}{\partial t}$ and an overdot denotes the derivative with respect to time, v represents the velocity defined according to the kinematic profile of the car.

From here on the procedure described in [1] is the same. The steps consist in neglecting the longitudinal inertia of all ropes can be neglected in Eq. (4) so that the model is reduced to two equations for each section of the suspension and compensating ropes. The Galerkin method is used to determine an approximate solution to the nonlinear partial differential equations of motion, the boundary conditions given by Hamilton Principle in [1] and the overall lateral in-plane and lateral out of plane displacements of each rope, with the following finite series:

$$\overline{V}_i (x_i, t) = \sum_{r=1}^{N} \phi_{ir} (x_i) q_{ir} (t). \tag{8}$$

$$\overline{W}_i (x_i, t) = \sum_{r=1}^{N} \phi_{ir} (x_i) z_{ir} (t). \tag{9}$$

where $\phi_{ir} (x_i) = \sin\left(\dfrac{n\pi}{L_i} x_i\right)$; $r = 1, 2, 3, ..., N$; with N denoting the number of modes, are the natural vibration modes of the corresponding i^{th} rope and $q_{ir}(t)$ and $z_{ir}(t)$; $r = 1, 2, ..., N$ represent the lateral in-plane and lateral out of plane modal displacements, respectively. The final set of 4xN ordinary differential equations for the lateral in plane and lateral out of plane direction are the following

$$\ddot{q}_{ir} (t) + 2\zeta_{ir} \omega_{ir} (t) \dot{q}_{ir} (t) + \sum_{p=1}^{N} \overline{K}_{irp} (t) q_{ip} (t) = \overline{f}_{ir}^{q} + N_{ir}\, q_{ir} (t). \tag{10}$$

$$\ddot{z}_{ir} (t) + 2\zeta_{ir} \omega_{ir} (t) \dot{z}_{ir} (t) + \sum_{p=1}^{N} \overline{K}_{irp} (t) z_{ip} (t) = \overline{f}_{ir}^{z} + N_{ir} z_{ir} (t). \tag{11}$$

The modal damping represented by the ratios ζ_{ir} and the undamped time varying natural frequencies of the element ω_{ir}. The $\overline{K}_{irp}$ is the stiffness matrix, $\overline{f}_{ir}^{q}$ and $\overline{f}_{ir}^{z}$ represent the excitation force terms and N_{ir} are the nonlinear terms.

Similarly, the equations of motion for the car, compensating sheave, and counterweight from Eq. (5) to Eq. (7) are transformed into the modal coordinates using the transformation

$$\vec{U} = [Y]\vec{S} \tag{12}$$

where $\vec{U} = \begin{bmatrix} U_{CR} & U_{CS} & U_{CW} \end{bmatrix}^{T}$ and $\vec{S} = \begin{bmatrix} S_{CR} & S_{CS} & S_{CW} \end{bmatrix}^{T}$ is a vector of modal-coordinates corresponding to the system comprising the car, compensating sheave, and counterweight, respectively. If $[Y]$ is the mass-normalized mode shape matrix, the following set of equations describing the vertical response of the car, compensating sheave and counterweight: in terms of the modal parameters

$$\ddot{S}_{CR}(t) + 2\zeta_{CR}\omega_{CR}(t)\dot{S}_{CR}(t) + \omega_{CR}^{2}(t)S_{CR}(t) = \left(\vec{Y}^{(1)}\right)^{T}\left(\vec{F} + \vec{\eta}\right). \tag{13}$$

$$\ddot{S}_{CS}(t) + 2\zeta_{CS}\omega_{CS}(t)\dot{S}_{CS}(t) + \omega_{CS}^{2}(t)S_{CS}(t) = \left(\vec{Y}^{(2)}\right)^{T}\left(\vec{F} + \vec{\eta}\right). \tag{14}$$

$$\ddot{S}_{CW}(t) + 2\zeta_{CW}\omega_{CW}(t)\dot{S}_{CW}(t) + \omega_{CW}^{2}(t)S_{CW}(t) = \left(\vec{Y}^{(3)}\right)^{T}\left(\vec{F} + \vec{\eta}\right). \tag{15}$$

where ζ_{CR}, ζ_{CS}, ζ_{CW} and ω_{CR}, ω_{CS}, ω_{CW} denote the modal damping ratios and the natural frequencies of the car, compensating sheave and counterweight, respectively, and $\vec{Y}^{(i)}$ is the ith mode shape vector. The $\vec{F} = \begin{bmatrix} \overline{F}_{CR} \\ \overline{F}_{CS} \\ \overline{F}_{CW} \end{bmatrix}$ is the excitation vector, and the $\vec{\eta} = \begin{bmatrix} \eta_{CR} \\ \eta_{CS} \\ \eta_{CW} \end{bmatrix}$ is a vector with components representing the nonlinear couplings with the lateral motions of the ropes.

4   CASE STUDY

A case study will be presented to illustrate the dynamic performance of an elevator system. The system comprises seven ($n_1 = 7$) steel wire suspension ropes and four ($n_2 = 4$) steel wire compensating ropes of mass per unit length $m_1 = 0.723$ kg/m and $m_2 = 1.1$ kg/m, having modulus of elasticity $E = 54535$ N/mm^2 and nominal diameters $d_1 = 13$ mm and $d_2 = 16$ mm, respectively. The modal damping ratios for the ropes are assumed as 0.3% across all modes and 10% across all the lumped modes. The height measured from the ground floor level to the center of the traction sheave is $h_0 = 88.875$ m, the car and counterweight height is $h_{cw} = h_{car} = 4.00$ m, travel height $h_{trav} = 80.70$ m, the car mass with full load is $M_1 = 4400$ kg, the mass of the compensating sheave is $M_2 = 600$ kg, and the mass of the counterweight is $M_3 = 3600$ kg. The high rise building is excited harmonically in the lateral in-plane at a frequency equal to the natural frequency of the

compensating rope when the car is passing through the middle of the travel height. In the lateral out of plane the building is excited at a much lower frequency. The elevator car is positioned at the bottom landing level and starts ascending to the top landing level with an acceleration of a_c=-1.1m/s^2 and the counterweight goes downward with an acceleration of a_{cw}=1.1m/s^2. Both the car and counterweight achieve a maximum speed of v=8m/s. The height measured from the bottom landing level to the center of the compensating sheave is given as $b_1 = 2.02$ m and the height from center of the traction sheave to the center of the diverter pulley is $b_2 = 0.80$ m. The results will be illustrated using computer animation and to demonstrate the nonlinear dynamic interactions between the components of the elevator system, during travel and when the system is stationary.

5   CONCLUSION

The equations of motion of a nonstationary elevator system following the kinematic profile dictated by the drive control algorithm comprising an elevator car, compensating sheave, counterweight, with suspension and compensating ropes excited by the high rise building motions are derived in this paper. These equations accommodate the nonlinear effects of the rope stretching in the lateral in-plane and the lateral out of plane directions. This model is used to predict the response of the system. While the motions of the structure are small, the rope is experiencing large lateral whirling motions. If the response of the ropes continue to grow impact phenomena in the hoistway might occur which may lead to excessive vibrations of the car and damage to the system components.

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Modelling and Simulation of a Nonstationary High-Rise Elevator System to Predict the Dynamic Interactions Between Its Components

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BIOGRAPHICAL DETAILS

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Stefan Kaczmarczyk is Professor of Applied Mechanics at the University of Northampton. His expertise is in the area of applied dynamics and vibration with particular applications to vertical transportation and material handling systems. He has been involved in collaborative research with a number of national and international partners and has an extensive track record in consulting and research in vertical transportation and lift engineering. He has published over 90 journal and international conference papers in this field.

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British Council for Offices (BCO) Guide to Specification 2014 Vertical Transportation

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Abstract. The British Council for Offices (BCO) has established over the years a well respected, referenced and utilised guide to best practice in the specification of commercial offices. Whilst the guide's usage is particularly prevalent in the London market, its relevance and value spans the United Kingdom and further afield.

September sees the publication of the sixth edition of the guide. Calling on the expertise of more than 100 leading industry professionals, all experts in their field, the guide establishes recommended benchmarks for all aspects of commercial property design.

A growing section of the guide deals specifically with vertical transportation and this addition sees the advice move another step towards closer alignment with other established guidance, particularly the Chartered Institution of Building Services Engineers (CIBSE) Guide D [1]. There are revised demand templates proposed that are based upon real world survey data. Car loadings have been reviewed and revised, again towards more realistic, observed levels. Guidance on goods lifts has been expanded along with additional comments on issues relating to fire-fighting lifts.

This paper provides an overview of the key technical elements of the guide, the thinking behind the advice, and trends for the future.

1   BACKGROUND

Whether one considers the design of effective vertical transportation strategies as an art, or a science, or simply a mystery, there should be no doubt as to the vital contribution lifts and escalators provide in making buildings work.

The *raison d'être* of most buildings is to provide a comfortable, safe environment within which people may live and work. People move around these buildings as blood flows around bodies; lifts are to a building as hearts are to bodies; a vital organ.

Buildings with insufficient lift and escalator provision quickly gain a reputation and lose tenants. Buildings with an overprovision cost their owners significant sums in the lower rent revenues generated by the smaller lettable area.

Much guidance has been published over the years to assist designers in developing appropriate vertical transportation systems to meet the predicted demands. From the seminal guides of Strakosch [2] and Barney [3], through to the foundation document of the CIBSE Guide D. The BCO guide has never purported to provide such detailed guidance as any of these three, but rather to provide the layperson reader with a key set of benchmark measures by which they may assess any design and challenge its provisions intelligently. The challenge therefore when drafting such a guide is to resist the temptation that is so commonly attractive to engineers to delve into the detail, and, with one's intended audience in mind, ensure the retention of appropriate simplicity at all times.

Luckily in this endeavour the review committee comprised the services of an able team of experienced peers in Mr. Simon Russett (Hoare Lea), Mr. Julian Olley (Arup), Mr. John Stopes (ex

WSP now The Vertical Transportation Studio) and Mr. Bill Evans (D2E International), with Mr. Neil Pennell (Land Securities) providing a technical chairmanship. The review process commenced in the summer of 2013 and concluded a few months ago.

2   THE NEW GUIDE

The last guide, published in 2009, provided the reader with significantly more information on vertical transportation than its predecessor, and this trend continues. Key considerations in drafting the new guide included:

1. Recognising the continuing trend towards increased occupancy densities
2. Adopting demand patterns based on actual building survey data
3. Aligning the advice with other established benchmarks, (e.g. CIBSE Guide D)
4. Recognising the prevalence of destination control (DC)
5. Taking another step away from the "interval"

2.1   DC or not DC

The previous guide recommended a different set of performance criteria for conventional control and destination control, which appeared in distinct, separate sections. The new guide recognises the increasing demand for destination control within the commercial office sector (particularly in London) and now proposes a single set of recommended performance criteria applicable to both destination and conventional control.

2.2   Waiting time vs. interval

Whilst the use of interval as a key performance criterion is well established, and indeed well justified by the historical complexity of mathematically calculating waiting time, its relevance in a "simple" guide such as the BCO is questionable. Users of lifts (and therefore layperson readers of the guide) intuitively understand the concept of waiting time better than interval and it has therefore been the goal of the guide to progressively move towards waiting time as a referenced criterion and away from the more complex measure of interval.

With destination control becoming the norm, the typical approach to lift traffic analysis now moves towards simulation and with simulation comes the ability to assess accurately and quickly the superior waiting time criterion.

The new guide therefore makes no recommendations as to appropriate interval times, instead noting the interval's demotion in favour of waiting time.

2.3   Population

It has long been recognised that the challenge for effective lift traffic design is not just in simulating the performance of the lift system itself but often more in accurately predicting the population of the building and the resulting demand patterns on the lifts.

As for previous issues of the guide, the BCO commissioned an extensive survey of building occupancy densities [4] which covered more than 380 properties all around the country.The survey concluded that, whilst there was some evidence to support the general feeling that densities were increasing significantly, this was not entirely supported by the findings. The overall mean density of surveyed properties was 1 workplace per 10.9 m^2 net internal area (NIA). Of the sample properties 38% fell within the range 8-10 m^2 (NIA), with 58% falling within the wider range of 8-12 m^2 (NIA).

Table 1 below shows that the highest densities are in the Corporate sector at 13.1 m^2 NIA per person and the lowest in the Financial & Insurance sectors at 9.7 m^2 NIA per peron. London and the South East have lower densities than may be expected which is thought to be due to the greater proportion of space allocated to lower density uses such as client entertaining and meeting room space.

Table 1 Breakdown of Results by Sector and Region

Sector	Density (m^2 NIA)	Region	Density (m^2 NIA)
Corporate	13.1	South East	12.7
Financial & Insurance	9.7	Wales	11.4
Professional Services	12.3	London	11.3
Public Sector	12.1	Midlands	10.2
Technology, Media & Telecoms (TMT)	10.5	North	10.1
		Scotland	9.7
		East	9.4
		South & South West	8.6

The BCO also undertook an analysis of data held by IPD[1] covering over 4 million m^2 in 823 properties from the private sector and over 4 million m^2 from the central government sector.

The trend from the whole data set during the relatively brief period of time from 2008 to 2012 showed very little change (Fig.1).

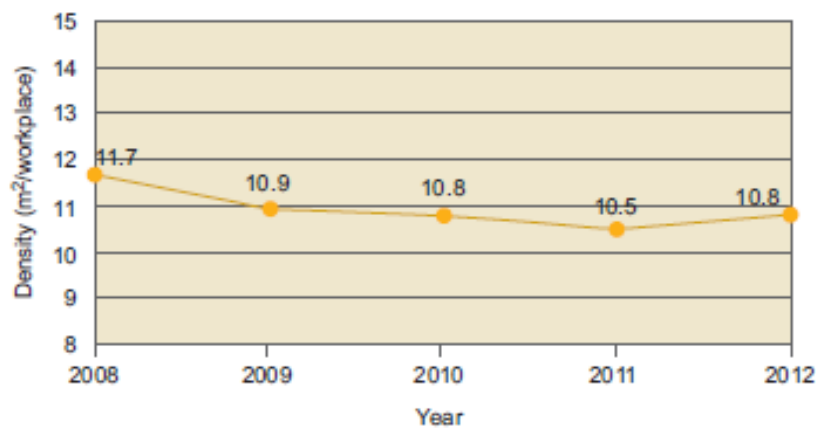**Figure 1 IPD data: overall mean density over time**

However when those buildings that appeared in all five data points were analysed (some 0.3 million m^2) a clearer trend of increasing density is observed (Fig.2). The BCO draw an implication from this trend that occupation densities may be slowing as they tend to a "level" beyond which perhaps the benefits of increased efficiency diminish.
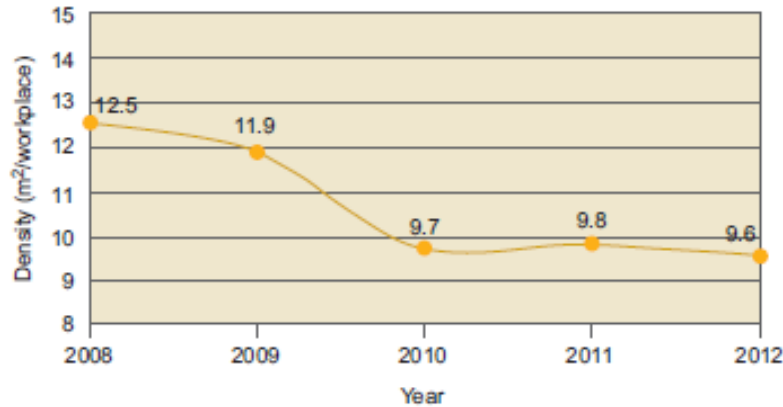
Figure 2 IPD data: overall mean density for the same buildings over time

The findings of the survey presented sufficient evidence to expand the range of recommended occupancy densities for lift traffic design. Previously the guide recommended designing to an occupancy of 1 person per 12 m^2 (NIA) and noted that this reflected a workplace density of 1 person per 10 m^2 (NIA) with a utilisation factor of just over 80%. The new guide retains this previous advice but now goes on to propose alternative criteria for high density offices, suggesting an effective density of 1 person per 10 m^2 (NIA), reflecting a workplace density of 1 person per 8 m^2 (NIA) with a utilisation factor of 80%.

It should be noted that, in the author's experience, clients or their advisors will often provide the occupancy density criteria that they wish the building and lifts to be designed to meet, as this often forms a key part of the marketing strategy and differentiates the building from its competition in the marketplace.

2.4   Demand profiles

As previously noted it was a key consideration of the BCO technical committee to align, where appropriate, the BCO advice with other established guidance, such as CIBSE Guide D.

In terms of demand on lifts, the previous guide had proposed designing to a morning uppeak of at least 15% of the design population in a five minute period, comprised of pure 100% up traffic. The recommended lunchtime profile was 12% of design population with mixed traffic components (i.e. up, down and interfloor).

Informal observation of lift traffic in buildings has suggested, for quite some time, that such a demand does not exist in reality. In 1996, Peters, Mehta & Haddon presented a paper [5] on lift passenger traffic patterns noting that morning traffic peaks were less marked than traditionally assumed and that lunchtime was becoming the busiest period for lift traffic. A Stanhope paper published in 2004 [6] also concluded, albeit based upon small sample sets and a methodology that was challenged at the time, that the demand proposed by the design criteria of the time was not observed in the real world.

Working patterns have evolved and eroded the rigid start and finish times of the past. Peak demand is rarely at such high levels and traffic never purely in the up direction. Lunchtime demand is normally greater than the morning demand, and the classic downpeak is now rarely observed.

Between 2007 and 2009 Peters Research Ltd undertook case studies of lift demand in a number of buildings. The result of their work is published within Chapter 4 of the CIBSE Guide D which proposes a set of modern office uppeak and lunchtime demand templates which correlate with

observed reality. The new BCO guide adopts the principles of these templates as revised recommendations and the changes are as tabulated in Table 2 below.

Table 2 Demand Profile Comparisons

Demand Criterion		BCO 2014	BCO 2009
Morning Uppeak	5-Minute Handling Capacity	12%	15%
	Traffic Mix	85% (UP) / 10% (DOWN) / 5% (IF)	100 (UP)
Lunchtime Peak	5-Minute Handling Capacity	13%	12%
	Traffic Mix	45% (UP) / 45% (DOWN) / 10% (IF)	42% (UP) / 42% (DOWN) / 16% (IF)[1]

The guide retains its previous advice to use multiple simulation runs to assess theoretical performance, and to utilise typical demand profiles that rise and fall around the specified peak handling capacity. Results as before should present the average values, as measured across the multiple runs, for the most intense five minute period.

The new guide now also recommends that performance should be tested with one lift out of service to understand the sensitivity of the system to failure and to indicate what level of reduced service would be provided in those circumstances.

2.5   Car loading

As many readers know, robust lift traffic analysis requires multiple data inputs and considerations. Moving the passenger demand profiles towards more realistic patterns could in itself be misleading unless other design parameters are also moved towards reality.

A point of some debate for some time has been the subject of car loading and whether its basis for calculation should be one of rated load or actual capacity. Again, informal evidence and possibly personal experience suggests that one rarely, if ever, finds oneself in, for example, a 13 person car with twelve other people.

CIBSE Guide D Table 3.1 proposes a set of rated vs. actual capacity numbers which are based on the premise that a human feels comfortable within an elliptical space of around 0.21 m^2. BS EN81-20 Table 6 defines the maximum available floor area for passenger lift cars of varying rated load and therefore one may quickly deduce a set of values that represent "full" cars, e.g. a 21 person car will be "full" when there are sixteen people within it.

However, whilst people may on occasion feel comfortable squeezing into a "full" lift car, this behaviour is not typically observed in the more gentile environment of an office. Here typical behaviour suggests a value of 80% of actual capacity to be more appropriate.

Consequentially the new BCO guide adopts this more realistic viewpoint and recommends that lift cars are not loaded to more than 80% of actual rather than rated capacity, assuming 0.21 m^2 per person.

2.6   Performance values

There are no proposed changes to the recommended performance times in terms of average waiting time and average time to destination, which remain as summarised below:

- Lifts should target an up-peak average waiting time across all floors served of no more than 25 seconds (s). Average waiting times of up to 30 s may be acceptable in cases where the average time to destination is 80 s or less.

- Lifts should target an up-peak average time to destination across all floors served of no more than 90 s. Average time to destination of up to 110 s may be acceptable where the morning up-peak average waiting time is less than 25 s.

- Lifts should target a two-way lunchtime average waiting time across all floors served of no more than 40 s.

2.7   All lifts to all floors

Another established principle of good lift system design, that of all lifts in a group serving all floors in the zone, has become justifiably challenged by the prevalence of destination control. Indeed, one of the attractions of destination control is it grants the designer the freedom to configure certain lifts in a group not to serve upper floors (thereby improving the net:gross floor area ratio) in a manner that is invisible to the user.

However, this approach should be used with care. It is intuitive that the fewer lifts one has serving certain floors, the poorer the performance may become. With current performance metrics being based on averages across *all* served floors it is possible for this measure to be compliant whilst average values to and from upper floors served by restricted numbers of lifts to be significantly outside the target.

The new guide draws the reader's attention to this and recommends that where all lifts do not serve all floors within a zone, the performance to and from those floors with reduced service is checked.

2.8   Destination control panels

The guide now contains some additional advice with regard to the number of destination input panels required. Whilst this should ultimately be established with the specialist lift designer, one panel per 60 passengers arriving in a 5 minute period provides a good starting point for design.

In all cases at least two panels should be provided in each lobby to provide a level of resilience in use should one fail.

2.9   Goods & fire-fighting lifts

The guide provides some new guidance on goods lifts noting that they are an important part of any commercial building and should be quantified, sized and located carefully. There is also a recommendation that dedicated goods lifts should be capable of travelling from the main access level to the highest floor served in around 50 - 60 s.

Additional general guidance is now offered on the appropriate use of fire-fighting lifts and evacuation lifts.

2.10 Additional content

The guide now contains new high level advice on other elements of vertical transportation design, such as:

- In-car multimedia screens

- Continuous operation of mobile telecoms and Wi-Fi connection

- Lift and escalator management and performance monitoring systems

- Car park shuttle lifts

- Vehicle, motorbike and bicycle lifts

- Lifting platforms

- Maintenance contracts and beneficial use

3   CONCLUSIONS

The 2014 guide takes another useful step towards better understanding of the key issues influencing vertical transportation planning. The fact that its updated advice on some of the fundamental issues is now starting to align well with other publications is encouraging and to be welcomed for this and future issues.

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BIOGRAPHICAL DETAILS

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Adam started his career in the lift industry 23 years ago with Otis in London, UK. After twelve years working in construction, service, modernisation and new equipment sales, he moved into the world of consultancy with Grontmij (formerly Roger Preston & Partners) and has subsequently worked on the design of vertical transportation systems for many landmark buildings around the world.

Adam is a past Chairman of the CIBSE Lifts Group and of the CIBSE Guide D Executive Committee. He is the current codes and standards representative for the CIBSE Lifts Groups and sits on the British Standards Institute MHE4 technical committee. He is also a member of the BCO vertical transportation technical review committee. Adam is currently the UK nominated expert for WG7 working on the revision of EN81-70.

The implications of the Lifting Operations and Lifting Equipment Regulations (LOLER) 1998 in Care Homes

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Abstract. Recent health and safety work by Environmental Health Officers from a North West Local authority has identified problems in relation to compliance with the thorough examination requirements of LOLER. The problem was particularly identified after health and safety audits in a number of sectors where lifting equipment is regularly used. When Officers asked for evidence of lift certification, a large proportion of the certification produced clearly did not comply with the requirements of LOLER, despite the examination certificate in some instances looking very similar to a 'thorough examination' and despite the fact that the duty holder believed that they had complied.

This research project particularly focused on the implications of LOLER within Care Homes. The overall aim of the project was to gain a further more detailed picture of what compliance levels are in care homes, in relation to 'thorough examination' of lifting equipment. Furthermore the aim was to determine if 'duty holders' within the residential care home setting, have sufficient knowledge and understanding of the requirements of LOLER in relation to thorough examination of lifting equipment in order to achieve compliance.

Overall the research found that compliance levels in relation to 'thorough examination' of lifting equipment within care homes was weak. In short the majority of sample 'thorough examination' reports returned as part of the research did not fully comply with the Regulations. Also although respondents in the main seem to have some understanding of the Regulations, further work must be done to ensure that awareness and understanding is improved. A main recommendation is to the Health and Safety Executive (HSE) and local authorities, recommending that they focus a campaign on raising awareness of LOLER and the thorough examination requirement with duty holders.

1   INTRODUCTION

Every year, there are many accidents to employees and service users from using work equipment in health and social care, for example, in relation to the use of hoisting equipment, the HSE reported that 163 hoisting accidents were reported to them under the Reporting of Injuries Diseases and Dangerous Occurrence Regulations (RIDDOR), between April 2001 and December 2007 [1]. They report that falls from hoisting equipment can occur for a variety of reasons including the selection of the wrong sling resulting in the risk of the person slipping through it, to failure of equipment due to poor maintenance. Ensuring that work equipment is well maintained is therefore an essential factor in reducing the risk of such accidents.

The Lifting Operations and Lifting Equipment Regulations (LOLER) were introduced in 1998 and impose duties on 'duty holders' in relation to the provision and use of lifting equipment and in particular it imposes duties in relation to thorough examination and inspection of lifting equipment.

Within Care Homes, numerous pieces of lifting equipment are used and fall under the scope of LOLER, including lifting hoists, stand aids, slings, bath hoists, lifting platforms and stair lifts. Other equipment such as reclining chairs and profiling beds are not within the scope of LOLER,

however requirements under the Provision and Use of Work Equipment Regulations (PUWER) 1998, to adequately maintain the equipment still apply.

Recent work by the Environmental Health department at a North West Local Authority has identified problems in relation to compliance with the thorough examination requirements of LOLER. It has been identified in a number of sectors where lifting equipment is regularly used, such as tyre and exhaust premises, car sales premises, warehouses and within the residential care sector, that some duty holders are confusing 'general maintenance/ servicing' with thorough examination. It has also been identified that some certification provided by lift companies, although it looks to be a thorough examination report, actually doesn't comply with the requirements of LOLER.

This project focused on compliance, knowledge and understanding within the care sector so that findings and practices within the same sector could be bench marked against one another. Additionally the implications of non-compliance with LOLER for this sector are arguably greater, considering the vulnerability of the users of lifting equipment within this sector.

The overall aim of this research project was to gain a further more detailed picture of what compliance levels are in Care Homes, in relation to thorough examination of lifting equipment (as required under LOLER). Furthermore the aim was to determine if 'duty holders' within the Residential Care Home setting, have sufficient knowledge and understanding of the requirements of LOLER in relation to thorough examination of lifting equipment in order to achieve compliance.

2   REVIEW OF LITERATURE

LOLER came into force in 1998 and replaced most of a range of sector based legislation on lifting equipment e.g. legislation on factories, offices, shops, railway premises and construction sites [2]. A specific requirement of LOLER is that lifting equipment must be 'thoroughly examined'. The requirement to thoroughly examine actually dates back to the introduction of steam power in factories, when there was a great number of explosions of steam boilers and it was discovered that a legal requirement to have the boilers regularly examined by a competent person did dramatically reduce the number of such incidents [3].

2.1   What is lifting equipment?

Under LOLER (Regulation 2) lifting equipment is defined as 'work equipment for lifting or lowering loads and includes its attachments used for anchoring, fixing or supporting it'. An accessory for lifting is defined as 'work equipment for attaching loads to machinery for lifting'. Examples of the types of lifting equipment and operations covered under the Regulations include; a passenger lift in an office block, a rope and pulley used to raise a bucket of cement on a building site, a bath hoist for lifting a resident into a bath in a nursing/care home, or, a refuse vehicle loading arm used for tipping. [4].

The Regulations apply to both employers and the self-employed who provide lifting equipment for use at work, or to persons who have control of the use of lifting equipment however they do not apply to lifting equipment to be used primarily by members of the public, for example lifts in a shopping centre [5]. The fact that equipment is designed to lift and lower a load doesn't necessarily mean that LOLER applies [6]. The equipment must be defined as 'work equipment' which is defined under PUWER 1998.

2.2 Thorough examinations, inspection and maintenance

In particular LOLER sets out detailed requirements in relation to the thorough examination of lifting equipment. A 'thorough examination' is defined by the HSE as a 'systematic and detailed examination of the lift and all its associated equipment by a competent person' [7] and its aim is to detect any defects which are, or might, become a danger to persons and for the competent persons to report such defect to the relevant persons.

Regulation 9 outlines requirements in relation to how often lifting equipment and accessories must be thoroughly examined.

Additionally under the Regulations, it may be that lifting equipment may need to be *'inspected'* by a competent person, between thorough examinations. The Approved Code of practice for LOLER [4] indicates that a suitable inspection should be carried out where a risk assessment has identified a significant risk to operators or other workers from the use of the lifting equipment. It indicates that inspections must be undertaken by a 'competent person' and that frequency and extent of the inspections required will depend on the potential risk from the equipment.

Routine maintenance is not the same as thorough examination and inspection and typically involves checking and replacing worn or damaged parts, topping up fluid levels, lubricating and making routine adjustments [8]. Maintenance is a requirement under Regulation 5 of PUWER 1998. Preventative maintenance is best used in order to preserve the operational integrity of the installation [10]. Ensuring that lifting equipment is routinely maintained can be cost effective for a duty holder, as it will ensure that equipment continues to operate as intended, and risks associated with wear or tear are avoided.

2.3 Confusion?

It has been reported that businesses generally had demonstrated a sound working knowledge of LOLER, however a number of business organisations have revealed limited knowledge of the requirements under LOLER, in particular small to medium sized businesses [10]. In research prepared for the HSE, [2] it was found that many were confused about the meaning of the terms 'inspection', 'thorough examination' and 'maintenance', including both equipment suppliers and duty holders. For example one equipment supplier within the research study explained how they found it hard grasping the difference between 'inspection' and 'maintenance'. The equipment supplier explained how they were still doing presentations 4 years on for their clients (from the introduction of the Regulations), stating that there is 'confusion and ignorance'. In another study it was reported that an area where additional advice was often sought from trade associations was in relation to the distinction between inspections and thorough examinations with one respondent in his study reporting '..there's an awful lot of confusion in the industry between thorough examination, inspection, and sort of the meaning of both' [10].

2.4 Competent person

As discussed, LOLER requires that the person undertaking a thorough examination and inspection of lifting equipment be a 'competent person'. The term 'competent person' is not defined in law, however the HSE's Approved code of Practice and Guidance document for LOLER defines the term competent person and states that a competent person should have

such appropriate practical and theoretical knowledge and experience of the lifting equipment to be thoroughly examined as will enable them to detect defects or weaknesses and to assess their importance in relation to the safety and continued use of the lifting equipment.

This Approved Code of Practice also states that the competent person must be 'sufficiently independent and impartial to allow objective decisions to be made'. The guidance explains that a competent person can be a member of their own organisation who has the necessary competence and need not necessarily be employed from an external agency. It indicates however that they must ensure they have the 'genuine authority and independence to ensure that examinations are properly carried out and that the necessary recommendations arising from them are made without fear or favour'. Interestingly it has been found that almost one half of users and over a third of suppliers (of lifting equipment) believed that inspection is always externally provided and formally reported [2].

This research concluded that if this is considered along those who see inspection as anything that involves checking health and safety features (over 60 %) one can see that this might well be seen as an onerous requirement and may explain why some are resistant to carry out inspection. Interestingly they highlight that this may add to people's opinions about the unnecessary bureaucracy of health and safety regulation.

2.5 Turn off or leave on?

Interestingly, there have been some concerns raised by some authors about the actions of individuals undertaking thorough examinations. Following the identification of any defects which are or could become a danger to persons, during a thorough examination, LOLER, Regulation 10 indicates that the person making the examination should 'notify the employer forthwith'. A recent health and safety prosecution by the City of London Corporation, heard in July 2012, involved the prosecution of a property management company, after statutory thorough examinations of two passenger lifts uncovered defects which required immediate attention. The engineer conducting the examination subsequently left a notice on site describing the defects and the timescale for repair. The management company acted upon the report the next day by arranging for repairs to be carried out but left the lifts still in use. Prohibition Notices were subsequently served by an Environmental Health Officer and consequently a prosecution was brought against the company [11]. The case has created debates amongst professionals within the lift industry. Cooper [12] following a recent meeting amongst fellow professionals indicated that the room was divided in opinion as to whether or not an engineer surveyor undertaking a LOLER examination under Regulation 9 should switch a lift off if an 'immediate' defect is identified. He indicates that he is of the opinion that this isn't a LOLER argument and sees it as a Health and Safety at Work Etc. Act one, in that the Act imposes duties on us all and if anyone identifies a dangerous defect that presents an imminent danger of death or injury to anyone he feels 'the decision is simple. Make safe and isolate'. Gilbert [13] writes similar opinions. He highlights that those conducting a thorough examination are relied upon by their client to provide appropriate information and advice about the potential danger from any defect. He questions however why it is that someone recognised as a competent person, can just walk out of a building leaving lifting equipment in operation, when they have just deemed it to be unsafe? What is interesting to note is that LOLER clearly place this duty on the employer/duty holder and not the competent person.

As discussed above, the term 'competent' person, is not defined in law, and although the term is defined in the Approved Code of Practice, there is no current 'database' of 'competent persons'. This is in contrast to for example the regulation of gas engineers. Under the Gas Safety (Installation and Use) Regulations 1998 for a gas engineering business to lawfully undertake gas work that is within the scope of the Regulations, they must be on the Gas Safe Register. It is clear that illegal gas work by unregistered engineers is taken seriously as can be seen by recent prosecutions brought by the HSE (e.g. see [14]). It could be said that such serious action being taken by the HSE will act as a deterrent to others from working on gas equipment illegally. In terms of the competency of

persons working on lifting equipment however, no such 'register' exists. Organisations can become members of associations such as the SAFed as a method of proving their competency to their clients, however this is not a legislative requirement. What is however clear is that the HSE and local authorities will take action against duty holders for failing to maintain lifting equipment and have equipment thoroughly examined (see [15]).

Interestingly is has been reported that 'competent person' is not a well understood phrase, with many suppliers and hirers (of lifting equipment) believing that their customers do not understand what competence means [2]. A suggested reason for this was that the term 'competent person' is used in several different pieces of legislation and there is a perception that the phrase means different things in the differing pieces of legislation, causing some confusion.

2.6 How LOLER applies in Care Homes

Within care homes, numerous pieces of lifting equipment and accessories are used and fall under the scope of LOLER, including lifting hoists, stand aids, slings, bath hoists, lifting platforms and stair lifts. Such lifting equipment is used to aid in the movement of patients and can also serve to reduce musculoskeletal risks to carers.

Most lifting equipment used within a care home will fall under the scope of LOLER since it can be defined as 'work equipment' and therefore will require maintaining in accordance with the Regulations. This means that the lifting equipment must be subject to a 'thorough examination' conducted by a competent person, either every six months or in accordance with an examination scheme and may also require inspecting and maintaining-for example, it is likely to be necessary that slings are subject to pre use checks.

3 METHODOLOGY

For this research two different data collection techniques were used:-

1. Firstly the collection of primary data via an email which was sent to local authorities across England and Wales asking for feedback on their experiences in relation to lifting equipment and thorough examination reports that do not comply with the LOLER 1998

2. Secondly, once information was gathered from a review of literature and the email to local authorities, the collection of primary data via an anonymous questionnaire survey sent to a number of Residential Care Homes throughout Greater Manchester. Prior to sending the final questionnaire to the chosen sample the questionnaire was both pre tested and piloted. As part of this survey respondents were asked to return an 'example' copy of one of their last thorough examination reports. These were further analysed in order to determine whether or not such reports complied with Schedule 1 of LOLER.

Clearly in research it is important that a valid percentage of the population is targeted. A sample population of 100 was calculated using Creative Research System (2010) online survey software [16]. Through the researcher's liaison with local authorities throughout Greater Manchester, it was known that there were approximately 400 Residential Care Homes throughout the area. Using the online software, at a confidence level at 95%, with a confidence interval (margin of error at 8.5) the sample size needed was calculated at 100.

Prior to undertaking this research, ethical approval was sought from the University of Salford's Research Ethics Committee.

4   RESULTS

4.1 Email to local authorities.

In response to emails sent, several local authority officers expressed concerns that they had encountered thorough examination reports that did not comply with schedule 1 of LOLER, one raised concerns in relation to the issue of 'competency', and another concern raised included the issue of whether or not a competent person should isolate equipment when a serious defect was found.   The feedback from local authorities, along with information gained from a review of relevant literature was then used to shape the format of the questionnaire.

4.2 Survey Responses

In total forty two survey responses were received. Two surveys returned were returned blank, both responding that the homes didn't have any lifting equipment. For the purposes of analysis, these two surveys were therefore not included. The response rate overall therefore was forty percent.

4.2.1 Job title

The first part of the survey asked for the job title of the person completing the questionnaire. Most respondents indicated that they were a manager (57.5%). 22.5% of respondents did not complete the 'job title' section and 20% indicated 'other' responses. Considering that the majority of respondents indicated that they were a 'manager', it was therefore expected that these respondents would have at least some understanding of the LOLER Regulations.

4.2.2 Awareness that certain lifting equipment must be 'Thoroughly Examined' and of what equipment needs such examination

95% of respondents indicated that they were aware that certain lifting equipment within their Care Home required regular thorough examination in accordance with LOLER. These results are not surprising considering that the LOLER Regulations were introduced in 1998 and considering that the use of lifting equipment is integral to the care industry.

Question two asked respondents to 'tick' which pieces of lifting equipment they thought required a 'thorough examination' in accordance with LOLER. This question was asked to determine respondents' understanding of the application of the Regulations. Ten different pieces of lifting equipment were listed, eight of which do require thoroughly examining (when the equipment is 'work equipment') and two of which do not require a thorough examination in accordance with LOLER. The results of the survey can be seen in Table 1 below:-

Table 1: Which equipment requires a 'thorough examination?'

Lifting Equipment	Percentage who thought that lifting equipment *required* a thorough examination
A lifting hoist (mobile) (Does require a thorough examination)	100%
Slings (Does require thorough examination)	75%
A lifting hoist (fixed) (Does require a thorough examination)	92.5%
Profiling beds and trolleys (Do not require a thorough examination)	42.5%
Stair lift (Does require a thorough examination)	90%
A Lifting platform (Does require a thorough examination)	87.5%
A riser recliner chair (Do not require a thorough examination)	27.5%
A passenger lift (Does require a thorough examination)	90%
A bath lift (Does require a thorough examination)	97.5%
A bath hoist (Does require a thorough examination)	97.5%

Out of the total number of respondents, only 25% answered the entire question correctly. This provides worrying evidence considering the extent of the use of lifting equipment within this industry.

4.2.3 Confidence that respondents understand the difference between a 'thorough examination' and a service/routine maintenance of lifting equipment

Question three asked respondents if they feel confident that they understand the difference between a 'thorough examination' and a 'service/routine maintenance' of lifting equipment. 87.5% ticked to say 'yes' (that they felt confident they understood the difference), 2.5% ticked 'No' and 10% ticked 'not sure'. These results suggest that the majority of respondents are clear on the difference between a 'thorough examination' and 'maintenance' which does not reflect what was discussed by Wright et al. [2].

4.2.4 Experience with competent person

Question four asked respondents to tick all answers which applied, in relation to what a 'competent person' usually did when their lifting equipment was thoroughly examined and any defects with the lifting equipment were found. 90% ticked to say that the competent person discusses verbally with someone on site immediately about the defects and how serious they are and 97.5% indicated that the competent person leaves a copy of the report on site. Worryingly one respondent indicated that the competent person will not discuss the examination with them or leave a copy of a report on site.

4.2.5 Training and knowledge and how respondents learnt of the requirements

The survey asked respondents whether or not they had received any health and safety training. The majority (87.5%) answered 'yes' (that they had received training) and 12.5% responded no. The survey then asked respondents to indicate what health and safety topics they had covered on their training. In total 62.5% gave responses to this question, the most common topics mentioned by respondents being:-

- Answers which discussed them covering 'all health and safety topics' (12 respondents)
- Moving and Handling/Manual Handling (11 respondents)
- COSHH (9 respondents)

Interestingly only three respondents mentioned LOLER within their responses.

Question six within the survey asked respondents how they learnt about the requirements in relation to 'thorough examination'. The majority of respondents, 55%, responded that they were self-taught by reading guidance documents. Additionally:-

- 42.5% indicated that they had learnt the requirements on a training course
- 40% had learnt through a recent visit by their local authority Environmental Health Officer/Enforcement Officer
- 22.5% indicated they learnt of the requirements through their insurance company, and
- 17.5% gave 'other' responses

4.2.6 Benefit from further guidance?

The survey also asked respondents if they feel that they would benefit from further guidance or training from their local authority on the requirements of LOLER. In response to this question, over half of respondents (52.5%) indicated that 'Yes' they would benefit from further guidance or training.

4.2.7 Opinions/views

The survey went on to ask respondents for their opinions/views on the requirement to have lifting equipment 'thoroughly examined'. On the whole most respondents responded positively to the question with answers such as:-

'It's essential and good management to have assets regularly checked and maintained'.

The majority of respondents mentioned 'cost' in their responses, examples being:-

'Very Costly but beneficial and also a requirement that all inspectors look at'.

(It is important to note that 'cost' was mentioned within the question as an 'example' therefore it is not unexpected that respondents would discuss cost within their answers).

Additional interesting points raised included:-

'I need a clear definition of 'competent person' What qualification is required to be a lift engineer?'

*'Costly, Some companies (e.g ****!!) try to pass their 'recommendations' as requirements.'*

'Yes-cost and accountability. We pay for a service-why is it not up to 'thoroughly examined' standards??'

4.3 Audit of returned thorough examination reports

All returned example thorough examination reports were then audited for compliance with Schedule 1 of LOLER.

4.3.1 Was a service record/maintenance record returned rather than a thorough examination?

Firstly all returned reports were audited to determine if they were clearly not a 'thorough examination' in accordance with LOLER, but were a service or maintenance record. The majority of reports returned were what looked to be a 'thorough examination report' however 14.3% of respondents returned what clearly was a service/maintenance record for the lifting equipment.

All respondents that returned service/maintenance records rather than thorough examination reports, all had also answered 'Yes' to question 3 of the survey (that they felt confident that they understood the difference between a 'thorough examination' and the 'service/routine maintenance' of lifting equipment) as discussed in 4.2.3 above. These results are interesting and suggest that although these respondents believe they understand the difference between a 'thorough examination' and 'routine maintenance' they in truth did not.

4.3.2 Analysis of the content of the thorough examination reports returned

Once a determination had been made as to whether or not the report returned looked to be a thorough examination report, those which were deemed to look like a thorough examination were then further analysed in order to determine if they complied with Schedule 1 of LOLER. Reports were deemed to comply with Schedule 1 of LOLER when they contained all the information specified within the Schedule.

In total 55.6% of the reports returned **did not** comply with schedule 1 of LOLER.

The most common information missing from certain reports included:-

- The date of the last thorough examination **(with 28% of returned reports not containing this information)**
- Details of the 'reason for the examination' I.e Whether it was a thorough examination, within an interval of 6 months under regulation 9(3)(a)(i); Within an interval of 12 months under regulation 9(3)(a)(ii); In accordance with an examination scheme under regulation 9 (3) (a) (iii);or after the occurrence of exceptional circumstances under regulation 9 (3) (a) (iv); **(with 33% of reports returned not containing this information)**
- (if such be the case) that the lifting equipment would be safe to operate **(with 33% of returned reports not containing this information)**
- The name, address and qualifications of the person making the report; that he is self-employed or, if employed, the name and address of his employer **(with 28% of returned reports not containing this information)**

Additionally reports were analysed to determine if there was a visible UKAS accreditation stamp on the report or if it was clear from the report that the company/engineer was a member of a relevant organisation such as SAFed. Only three of the reports contained a UKAS accreditation stamp or indicated membership of a relevant association. The three reports which contained UKAS accreditation or evidence of membership of a relevant association, all complied with Schedule 1 of LOLER.

5   DISCUSSION

5.1 Knowledge and understanding of LOLER and 'thorough examination'

As discussed, it was not surprising that the majority of respondents were aware that certain lifting equipment required regular thorough examination in accordance with LOLER. It was however surprising and concerning to find that only 25% of respondents knew which pieces of equipment

did/didn't fall under the scope of LOLER, with 25% of respondents believing that patient slings did not require thorough examination. These results are concerning as every year there are numerous accidents involving hoisting, which may well have occurred due to failure of equipment due to poor maintenance. The HSE have produced several guidance documents in relation to LOLER and thorough examination, and in particular have produced two leaflets specifically aimed at the care sector; Getting to grips with hoisting people [1] which discusses hoisting and in particular discusses slings and the requirements in relation to thorough examination and; the more recent leaflet, How the Lifting Operations and Lifting Equipment Regulations apply to health and social care [6] which gives specific pictorial examples of the types of lifting equipment that require thorough examination. The results of this research therefore suggest that knowledge of the application of LOLER in terms of what type of equipment requires thoroughly examining is poor.

The results of this research also suggested that the majority of respondents felt that they were clear on the difference between a 'thorough examination' and 'maintenance' of lifting equipment. Interestingly however, several of the respondents who indicated that they did feel that they understood the difference, actually returned a service/maintenance record rather than a thorough examination report. This indicated that although they *thought* they understood the difference, in reality they did not. These results are comparable with Wright et al [2] who in their research prepared for the HSE, found that many were confused about the meaning of the terms 'inspection', 'thorough examination' and 'maintenance'.

In this study, although the majority of respondents felt confident that they understood the difference, there are still clearly a number of persons who do not understand the difference between a' thorough examination' and 'routine maintenance'.

5.2 Experience with the competent person

In relation to respondent's experiences with competent persons conducting a thorough examination, it was encouraging to find that 90% ticked to say that the competent person discusses verbally with someone on site immediately about any defects found and how serious they are and 97.5% indicated that the competent person leaves a copy of the report on site. This is encouraging as it suggests that the competent person referred to by the respondents are acting in line with Regulation 10 of LOLER, which requires the person making the examination to notify the employer forthwith of any defect which is or could become a danger to persons and which requires a report of thorough examination in writing to be made as soon as practicable. Worryingly however one respondent (2.5%) indicated that the competent person will not discuss the examination with them or leave a copy of a report on site.

Although it is reassuring to find that the majority of respondents have indicated that the competent person will discuss verbally with someone on site the defects and will leave a report, this raises the debate as to whether or not a competent person, should 'switch off' or 'take out of use' a piece of lifting equipment or accessory where a serious defect has been found, or whether this should be left to the responsibility of the duty holder. This topic was not explored in detail within this research and is potentially a further area of study.

5.3 Training and knowledge

It was not unexpected that the majority of respondents had received some health and safety training and neither was it surprising that moving and handling/manual handling was one of the most mentioned topics considering that a major role in the care sector is the moving and handling of patients, which if not conducted correctly may result in severe injury.

Interestingly only three respondents mentioned LOLER within their responses. This could be an indication that either the majority of respondents have not been specifically trained on 'LOLER', perhaps training on other topics has been more prevalent then specific training on LOLER, or it may be that LOLER has been discussed as part of wider 'moving and handling training'. Further study into the details of training courses attended by respondents would assist in determining the level of training on the subject.

5.4 How did respondents learn of the requirements and do respondents feel that they would benefit from further guidance off their local authority?

The results from this research suggested that the majority of respondents have learnt of the requirements of LOLER by 'self-reading' guidance documents. This is not unexpected considering that the HSE, have produced many guidance documents for the care sector which are available free online. Only 40% of respondents had indicated that they had learnt the requirements through a recent visit by their local authority Environmental Health/Enforcement officer. This may be due to the fact that proactive inspections are becoming less and less frequent by local authorities, following the emphasis by the Government on deregulation and 'reducing the burden' on businesses.

Additionally just over half of respondents expressed that they would benefit from further guidance from their local authority. This may therefore be an area where local authorities may wish to focus some resource in order to improve compliance.

5. 5 Opinions/Views

The final part of the questionnaire survey asked respondents for their views on the requirement to have lifting equipment thoroughly examined. Most respondents responded positively to the question. One notable point raised by one respondent was in relation to needing a clear definition of the term 'competent person' with the respondent asking what qualifications are required to be a lift engineer? This corresponds with what was found by Wright et Al. [2] who reported that 'competent person' is not a well understood phrase.

It could be argued that the introduction of a 'register of competent persons' in relation to lifts may make it easier for the duty holder to ensure that the person they chose to use is competent and additionally may reduce the frequency of lift companies/competent persons not complying with the requirements of LOLER.

5.6 Audit of the returned thorough examination reports

The returned thorough examination reports were audited and highlighted some interesting results. As discussed above, it was noted that several of the reports returned were not in fact thorough examination reports. They clearly were service/maintenance records.

Of those reports returned, 55.6% of the reports *did not* comply with Schedule 1 of LOLER with important information missing on some reports. Numerous reports did not contain details of the qualifications of the competent person, however this was not unexpected considering that there are no specific 'qualifications' that a 'competent person' must possess to prove competency. Again, this could become confusing for the duty holder, who will more than likely not have the knowledge and understanding to be able to determine if the 'competent person' they are employing is in fact 'competent'.

Another interesting point that the research has shown was that out of those reports audited, three reports contained evidence of accreditation with UKAS or evidence that that lift company/competent person was a member of a relevant association. Interestingly, all three of these

reports complied with Schedule 1 of LOLER. These results may be of interest to non-accredited or non-affiliated lift businesses, who may want to ensure that they can compete with such companies.

6   CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The overall aim of this research project was to gain a further more detailed picture of what compliance levels are in Care Homes, in relation to thorough examination of lifting equipment (as required under LOLER) and to determine if 'duty holders' within the Residential Care Home setting, have sufficient knowledge and understanding of the requirements of LOLER in relation to thorough examination of lifting equipment in order to achieve compliance.

From surveying a sample of Care Homes throughout Greater Manchester, this study came to several notable conclusions. The research found that the majority of respondents have some awareness of LOLER and the fact that certain lifting equipment required thoroughly examining in accordance with the Regulations, however it has found that respondent's knowledge in terms of which types of equipment did/didn't fall under the scope of LOLER was poor. For example, 25% of respondents thought that patient slings did not require a thorough examination-a conclusion that has proved to be concerning. The survey also found that many respondents felt that they were confident that they understood the difference between a 'thorough examination' and 'maintenance' of lifting equipment, although there was evidence that some respondents did not understand the difference.

With regard to respondent's experience with 'competent persons' it was positive to find that the majority of competent persons discuss verbally with someone on site immediately about any defects found during a thorough examination and that the majority leave a copy of the examination report on site suggesting that the majority of competent persons are acting in line with Regulation 10 of LOLER.

With regards to training it was found that the majority of respondents had received health and safety training but only a small proportion 'mentioned' LOLER as being a topic covered on their training. Additionally the survey found that the majority of respondents were 'self-taught' on LOLER and 'thorough examination', by reading guidance documents. The survey also found that over half of respondents thought that they would benefit from further guidance or training from their local authority. Additionally respondents were asked for their opinions/views and several interesting points were raised, including one particular respondent wanting clarity on the term 'competent person'.

Interestingly the research also found that the majority of thorough examination reports audited for compliance with Schedule 1 of LOLER, *did not* comply with the Schedule.

Overall, the research found that compliance levels in relation to 'thorough examination' of lifting equipment within care homes was poor with the majority of reports being returned not complying with the Regulations. Also although respondents in the main seem to have some understanding of the Regulations, further work must be done to ensure that awareness and understanding is improved. The research suggests that respondents (who in the main were managers and who are most likely therefore to be responsible for ensuring that lifting equipment is appropriately examined and maintained) do not have sufficient understanding of the requirements of LOLER in relation to thorough examination of lifting equipment in order to achieve compliance.

6.2 Recommendations

It is recommended therefore that:-

- The HSE and local authorities focus a campaign for the care sector on raising awareness of LOLER and the thorough examination requirement.
- The HSE and local authorities also work collaboratively to address 'competent persons' and lift companies who are producing certification that does not comply with Schedule 1 of LOLER
- The feasibility of a 'register of competent persons' in relation to lifts (i.e. similar to the Gas Safe Registration Scheme) be further explored and if feasible, devised. This could be devised by industry with HSE backing.

6.3 Limitations of this research project

Although a postal survey was the main preferred method of data collection within this research project due to time constraints and due to the fact that a larger population could be targeted, it must be noted that the use of postal questionnaires does pose some limitations such as low response rates. Low response rates can increase the chance of research bias. It is therefore recommended that this research be expanded to include a larger sample of Care Homes.

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BIOGRAPHICAL DETAILS

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Under Lifted Buildings in the Middle East

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Abstract. This paper explains and discusses under lifted buildings located in the Middle East. Three case studies are presented. Solutions or partial solutions are presented for the under lifted conditions

1. INTRODUCTION

Prior to the fall of 2008, the Middle East experienced a real estate boom of incredible proportions. In the construction frenzy prior to the bursting of the real estate bubble, many buildings were built without receiving advice from lift traffic engineers. In some cases a lift consultant was retained but his recommendations were ignored because too many lifts were recommended.

These under lifted buildings were either vacant or only partially occupied for several years. However, starting around 2013 the economy in parts of the Middle East started improving. The improvement has been particularly strong in Dubai. As the occupancy of these under lifted buildings increased, the inadequacy of the lift installations became apparent. Building owners and managers began to request help in solving the traffic handling problems in their buildings.

Three examples of under lifted buildings in Dubai are presented along with recommendations on how correct or at least improve the traffic handling inadequacies of these buildings.

2. CASE STUDY A

Building A is a multi-tenant office building located in Dubai. The building has three parking floors below the ground floor lobby, six parking floors above the lobby, and forty one office floors. The building has seven total lifts that serve all 51 stops. The 7 lifts are split into two banks. A 3 car group of panoramic lifts with a capacity of 1000kg and a speed of 2.5 m/s and a 4 car bank of conventional lifts with a capacity of 1000kg and a speed of 4 m/s.

Building A was completed prior to collapse of the real estate market in January of 2009. The building was largely unoccupied until the middle of 2012. The Dubai economy started to recover in 2012 and the population of Building A started to increase. By the beginning of 2013 the tenants were complaining about long waiting times.

Each typical floor has 696 square meters of Net Internal Area (NIA). If one assumes that Net Useable Area of this building is 80% of NIA, then each floor has a potential population of 46 persons [1].

2.1 Building A Problems

The most obvious problem was there were not enough lifts. CIBSE Guide D recommends, as a rule of thumb, 1 lift for every 3 floors [2]. 51 floors divided by 3 would suggest that 17 lifts would be required. However, only 7 were installed.

Since both groups of lifts served the same floors, passengers would place a hall call for each of the groups. Initially, passengers were placing two hall calls for each service request. Later, out of frustration, passengers would press both the up hall call and the down hall call of each group. In this way, each true hall call was accompanied by three false calls.

Each car park level is also a building entrance. Therefore, this building has 10 entrance lobbies.

Table 1 shows the impact of adding additional entrance levels to an 18 floor building with 6 lifts. Simulation software was used generate Table 1 [3]. Building A is under lifted with one entry level. However, observe the impact that additional entry levels have on waiting times and times to destination. For this reason CIBSE Guide D recommends that parking floors be served by separate lifts that do not serve office floors [2].

Table 1

	Up Peak		Lunch	
	AWT	ATT	AWT	ATT
Lobby	12.3 s.	75.9 s.	23.1 s.	64.1 s.
Lobby + 1 Parking	33.3 s.	77.4 s.	32.3 s.	72 s.
Lobby +2 Parking	38.0 s.	77.9 s.	43.1 s.	75.1 s.
Lobby + 3 Parking	48.8 s.	80.3 s.	53.0 s.	83.3 s.

2.2 Building A Solution

For economic reasons, the control system could not be replaced. Therefore, the low cost solution for building A was to split the office floors into 2 zones. The low speed lifts would serve the lower zone and the high speed lift would serve the upper zone. Additionally, cars were assigned to specific parking floors. This reduced the number of entrance levels for each group and eliminated the possibility of registering calls to two groups. Tables 2 and 3 below demonstrate the results of this 2 bank system based on 25 persons per floor and 20% absenteeism. Please note this traffic level would represent a 54% occupancy level. Peters Research Modern Up Peak and Modern Lunch Templates, an option in simulation software were used to evaluate the proposed solution [3].

The 3 car group would serve floors B3, B2, B1, L, P1, and office floors 1 - 19.

Table 2 3 Car Group

Up Peak		Lunch	
AWT	ATT	AWT	ATT
32.2 s.	69.8 s.	48.6s.	67.3s

The 4 car group serves floors L, P2, P3, P4, P5, P6, and office floors 20 – 41.

Table 3 4 Car Group

Up Peak		Lunch	
AWT	ATT	AWT	ATT
29.3 s.	73.6 s.	39.8 s.	72.5 s.

2.3 Building A Comments

This building simply does not have the required number of lifts to deliver good service. The modifications to the existing system greatly improved service. However, if the building occupancy reaches a level above 54%, traffic handling problems will return.

Permanent solutions could include installing additional lifts to serve the parking levels, converting the existing lifts to a multi-car system, and installing more tower lifts.

3. CASE STUDY B

Building B is a single tenant office building occupied by a builder and developer. The building was completed in 2008. The building was lightly occupied until 2013. The building has 28 floors. There are 3 parking levels below the main lobby, a ground level lobby, 5 parking levels above the lobby, and 19 office levels.

3.1 Building B Problems

Tenants were complaining of long waiting times. Waits of over 5 minutes were reported. The building was equipped with 6 lifts, each with a capacity of 1000kg and a speed of 4 m/s. All of the lifts served all of the floors. The lift control system had the Early Call Announcement feature which would illuminate a hall lantern and sound a chime immediately upon hall call registration. The car assignments were constantly being reassigned due the traffic levels in relation to the number of lifts. The constant sound of chimes and flashing hall lanterns created a high level of confusion.

The owner believed that the traffic problems were related to poor maintenance. A survey was conducted and the owner was advised that the maintenance was adequate. However the traffic problems were the result of the building being under lifted.

The building owner provided a list of the occupants on each of the occupied floors. Not all floors were occupied. However the owner anticipated that the building would achieve a 90% occupancy rate within two years.

Using the occupancy information provided by the owner, a traffic simulation was conducted using the Peters Research Modern Office Templates. The results were the following:

Worst Average Waiting Time during any 5 minute period during Up Peak: 322.0 s.

Worst Average Waiting Time during any 5 minute period during Lunch: 96.8 s.

The simulation results were consistent with the tenant observations. The system was saturating.

3.1 Building B Solutions

A four phase solution was proposed as follows:

Phase 1: Install a Destination input overlay on the 6 tower cars.

Phase 2: Modernize the 6 tower lifts using a destination input controller and a high performance door system.

Phase 3: Install 4 car park lifts with a speed of 1.7 m/s and a capacity of 1000kg.

Phase 4: Modify the tower lifts so that they do not service the car park levels.

For each of the four proposed phases, simulation software was used to model the anticipated performance of the lift systems during Up Peak and Lunch using templates from Peters Research. The results are as follows:

At completion of Phase 1:

Worst Average Waiting Time during any 5 minute period during Up Peak: 47.8 s

Worst Average Transit Time during any 5 minute period during Up Peak: 55.8 s

At completion of Phases 2, 3, and 4 with an occupancy level of 90% on all floors:

Tower Lifts Up Peak:

Worst Average Waiting Time during any 5 minute period: 34.1 s

Worst Average Transit Time during any 5 minute period: 53.1 s

Tower Lifts Lunch:

Worst Average Waiting Time during any 5 minute period: 49.4 s

Worst Average Transit Time during any 5 minute period: 45.3 s

Car Park Lifts Up Peak:

Worst Average Waiting Time during any 5 minute period: 16.2 s

Worst Average Transit Time during any 5 minute period: 27.4 s

Car Park Lifts Lunch:

Worst Average Waiting Time during any 5 minute period: 21.3 s

Worst Average Transit Time during any 5 minute period: 31.4 s

3.3 Building B Comments

Building B is another example of the need to provide separate lifts for the car park floors and for the office floors of a building.

4.   CASE STUDY C

Building C is a building that was substantially completed in 2008 but was vacant until 2013. It was developed by the same firm that developed Building A. The developer was concerned that this building might have problems similar to those of Building A and asked for an analysis.

Building C is a 25 story office building. The building has 17 office floors located above a podium of 4 below ground parking levels, a ground level lobby, and 3 levels of above ground parking. The 17 office floors and 8 entrance levels were served by 5 passenger lifts each with a capacity of 1150kg and a speed of 2.5 m/s. Each of the office floors was expected to have 66 occupants when fully leased.

4.1 Building C Problems

Based on the rule of thumb that there should be one lift for every 3 floors and the suggestion that car park levels should be serviced by separate lifts, the building appeared to be under lifted.

A traffic analysis using Up Peak and Lunch templates from Peters Research was conducted. Figure 1 is a plot of the queue lengths during Up Peak.
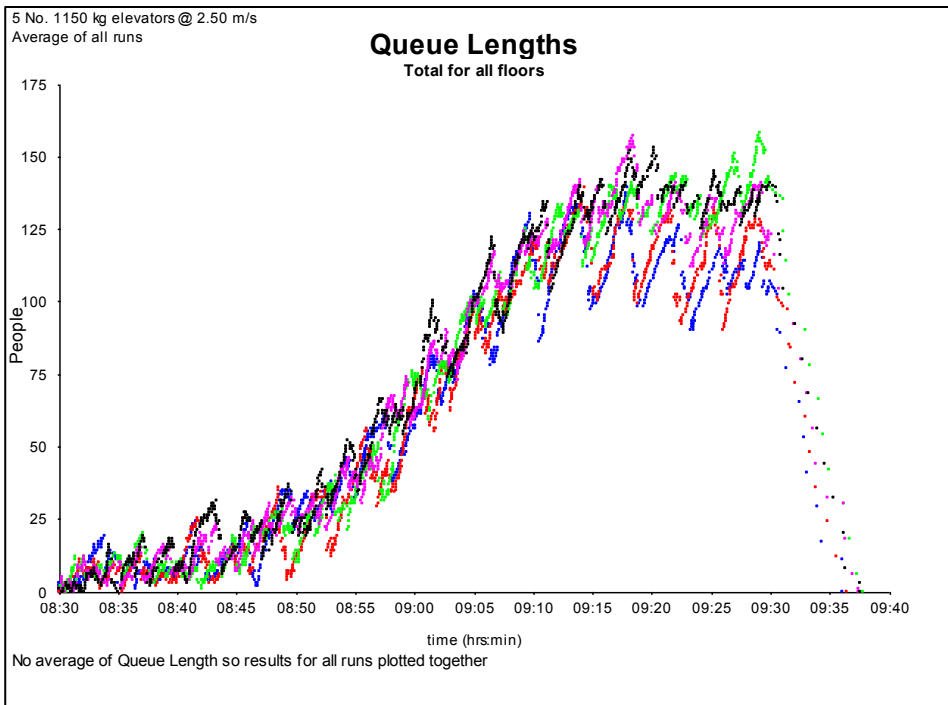
Figure 1Queue Lengths Up Peak
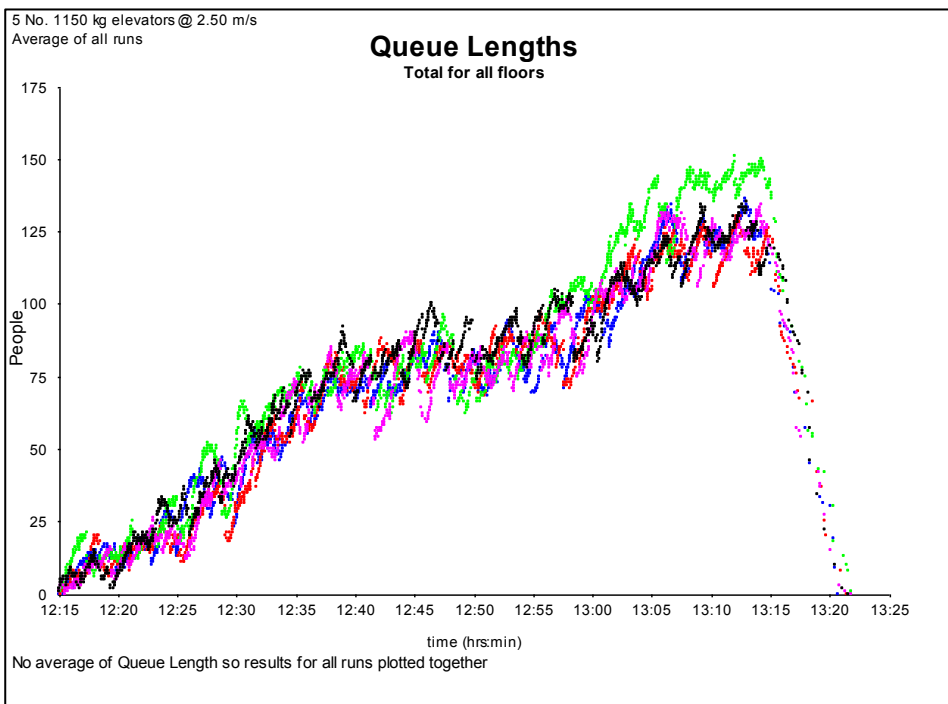
Figure 2 is a plot of the queue lengths during Lunch.

Figure 2 Queue Lengths Lunch

Figures 1 and 2 show a system that is saturated.

4.2 Building C Recommendations

The 5 lifts are fitted with a conventional group control system. A simulation using templates but based on the lifts serving only the lobby and the office floors indicated the following:

Up Peak:

Worst Average Waiting Time during any 5 minute period: 136.4 s

Worst Average Transit Time during any 5 minute period: 88.3 s

Lunch:

Worst Average Waiting Time during any 5 minute period: 64.8 s

Worst Average Transit Time during any 5 minute period: 83.8 s

The simulations were run a second time using a proprietary destination input system. The following are the results:

Up Peak:

Worst Average Waiting Time during any 5 minute period: 37.6 s

Worst Average Transit Time during any 5 minute period: 67.1 s

Lunch:

Worst Average Waiting Time during any 5 minute period: 57.5 s

Worst Average Transit Time during any 5 minute period: 57.9 s

A destination input control system was recommended for the 5 lifts. Additionally, a bank of 3 lifts was proposed to serve the car park areas.

The addition of 3 car park lifts was rejected as not being feasible for structural and economic reasons.

An alternative method of serving the car park area was proposed; Valet Parking. In Dubai, labor costs are very low in comparison to lease rates. Valet Parking could be viewed as a luxury feature whilst inexpensively solving a vertical transportation problem.

4.3 Building C Comments

Building C is another example of the need to have separate lifts for the car park floors and separate lifts for the office floors of a building. However, in this building a method that involves Valet Parking in lieu of Vertical Transportation was recommended.

5. CONCLUSIONS

Many buildings in the Middle East are built with an office tower on top of a parking podium. In most cases, the parking podium and the office floors are parking podium are served by the same lifts. Dozens if not hundreds of similar buildings will encounter traffic handling problems as their occupancy increases. This paper offers some partial remedies for these problems. The only way to achieve a good vertical transportation performance is to perform a professional traffic analysis during the design stage.

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Human Body Size in Lift Traffic Design

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Keywords: Lift traffic design, human factors, level of service.

Abstract. Calculations and simulations in lift traffic design assume a certain passenger capacity of a lift, i.e. the maximum number of passengers the lift can accommodate. Industry standards define the passenger capacity by dividing the rated load of a lift by the average weight of a passenger. An alternative approach divides the car area by the area of a body ellipse, which models the space requirement of a passenger. Lift safety standards assume a significantly smaller area per passenger than the typical body ellipse. This implies that area-based passenger capacity is smaller than load-based, and, therefore, also the lift group handling capacity becomes smaller. This paper reviews statistics of human body dimensions from existing literature. Body ellipses drawn from the dimension distributions as well as the typical body ellipse are used to study how many passengers fit in standard-sized lifts. Traditionally, lift group service quality has been evaluated by passenger waiting time and time to destination. This paper proposes a new service quality metric for the area available to passengers. Body sizes vary from one country to the next, in different kinds of buildings, as well as they evolve over the course of time. Therefore, the definition of passenger capacity as well as adequate space for comfortable travel needs to be periodically redefined according to local practices.

1   INTRODUCTION

Lift traffic analysis is based on passenger capacity, which is the maximum number of passengers a lift car can accommodate. Industry standards define passenger capacity by dividing the rated load of a lift by the average passenger weight, which is, for example, 75 kg in Europe [1], 72.5 kg in the US [2], and 67 kg in Japan [3]. Thus, a particular rated load results in different passenger capacities depending on the standard. EN 81-1 also defines the minimum and maximum available car area for each rated load to prevent overloading of the car. The available car area per passenger decreases as the rated load increases. For example, the area per passenger in a 100 kg (one person) lift is at least 0.28 m^2 and at most 0.37 m^2 but in a 1600 kg (21 persons) lift it is 0.155 m^2 and 0.170 m^2 [1].

An alternative approach defines passenger capacity as the maximum allowed area of a lift divided by the 0.21 m^2 occupancy area of a passenger weighing 75 kg [4]. The area of a passenger is taken as the area of the Fruin body ellipse with width 600 mm and depth 450 mm, which includes an additional 20 mm space in width and 120 mm in depth [5]. However, the Fruin body ellipse was derived for a large 95th percentile male with respect to maximum body breadth and depth [6, 7], but the 95th percentile weight was in the 1950s about 90 kg [8]. Since it is highly unlikely that only men of such size wait for a lift at the same time, also the area-based passenger capacity should be defined with the average passenger dimensions rather than the 95th percentile dimensions. The surveys reported average weight 73 kg [8] as well as body breadth 530 mm and depth 290 mm [6]. The area of a body ellipse according to these dimensions and the additional space becomes 0.177 m^2. Then, the passenger capacity of a 1600 kg lift becomes 20.1 passengers with 0.177 m^2 occupancy area instead of 16.9 passengers with 0.21 m^2 occupancy area [9].

The body size distribution of the target population using the lifts depends on the gender as well as the building type and its geographical location. In general, office buildings are occupied by adults but hotels and residential buildings by children, adults and elderly people. In the Far East, people are smaller in size compared to western countries. This paper studies how many passengers a lift

can physically accommodate and proposes a new service quality metric for the space available to the passengers, which overcomes the pitfalls of area-based definition of passenger capacity.

2   HUMAN FACTORS AFFECTING LIFT TRAFFIC DESIGN

Maximum body breadth and depth are commonly called clearance dimensions [7]. Still to date, the distributions of these dimensions for males originate from a survey conducted by the US Air Force in the 1950s, according to which the 95th percentile maximum body breadth and depth were 580 mm and 330 mm, respectively [6]. These 95th percentile clearance dimensions were the basis of the Fruin body ellipse, which contains 20 mm additional space in width and 120 mm in depth for clothing and personal space [5]. On the other hand, Pheasant body ellipse was defined for designing workspaces and taking into account ergonomics by adding 50 mm both in width and depth to the 95th percentile clearance dimensions [7]. The areas of the Fruin and the Pheasant body ellipses are 0.212 m^2 and 0.189 m^2, respectively. Thus, even though they are based on the same clearance dimensions of the 95th percentile male, their areas differ clearly due to different requirements for the space around the body.

The clearance dimensions have not been measured since the original US Air Force survey, but several surveys report statistics on shoulder breadths [7, 8] and waist circumferences [8, 10, 11]. In addition, the Air Force surveys [6, 8] summarize measurements of relatively young males of an average age of under 30 years who were fitter than the general population [10, 11]. In comparison, the median (95th percentile) waist circumference was 80.5 cm (95.2 cm) in the Air Force survey [8] while the 1960s' survey of the general population reported a median 88.3 cm (95th percentile 109.0 cm) for males aged 18-79 years, 79.2 cm (99.8 cm) for males aged 18-24 years, and 85.6 cm (105.7 cm) for males aged 25-34 years [10]. Thus, males of age between 18 and 24 years in the general population corresponded closely to the Air Force personnel at that time. On the other hand, overweight and obesity have become more and more common in western countries. In the US, a recent survey indicates that the median (95th percentile) waist circumference among males has increased to 99.4 cm (128.1 cm) [11], thus 10 cm increase in the median and 20 cm increase in the 95th percentile compared to the data of the 1960s.

Table 1. 95th percentile points of body dimensions in some countries [7]

Country	Shoulder breadth [mm]		Chest depth [mm]		Abdominal depth [mm]	
	Men	Women	Men	Women	Men	Women
Brazil	490	N/A	275	N/A	305	N/A
France	515	470	280	295	320	305
Hong Kong	470	435	235	270	270	280
India	440	N/A	205	N/A	235	N/A
Japan	475	395	230	235	255	240
The Netherlands	520	445	330	350	375	360
Poland	475	410	275	285	310	295
Sri Lanka	400	360	205	210	235	220
Sweden	510	425	255	300	290	310
United Kingdom	510	435	285	295	325	305
United States	515	440	290	300	330	310

Body sizes also vary a lot between geographical areas. Table 1 shows the 95th percentile shoulder breadth, chest depth and abdominal depth in different countries [7]. In the western countries, shoulder breadths of men vary from 510 to 520 mm but, for example, abdominal depths have greater differences, from 290 to 375 mm. On the other hand, Asians are clearly smaller in size compared to westerners. As extremes, the area of the body ellipse[1] of Dutch men equals 0.153 m^2, but the area of Sri Lankan workers is only 0.074 m^2. These are considerably smaller than the areas of the Fruin and the Pheasant body ellipses.

The maximum number of passengers that actually pack into a lift depends not only on body sizes but also on human behaviour. People prefer to keep a distance from one another within the personal space around them [12]. The desire for personal space (probably) explains the observation that lifts are not packed more than 63-76% of the load-based passenger capacity [13]. For example, if a 1600 kg (21 persons, 3.56 m^2) lift is loaded within this range, the number of passengers inside the lift ranges from 13 to 16 passengers and the area per passenger from 0.223 to 0.274 m^2. This corresponds to comfortable loading, where passengers do not cross the touch-zone of others and the available area per passenger equals 0.279 m^2 [5].

Also passengers' motivations affect their decisions whether to board a lift or not. According to an old experiment, test persons comprising only women packed in a lift as tightly as 0.139 m^2 per person, and a mixed group of men and women achieved 0.167 m^2 per person [5]. If the passengers know each other or they are leaving an office building in the evening, lifts have been observed to carry so many passengers that the available area reduces to 0.14 m^2 per person [10]. A tight social group (a family, a couple) prefers to keep together: either the group does not board if the available space is not sufficient for all members, or the last member to board pushes in even if the lift is already crowded. At football stadiums in the UK, extreme crowd densities have been observed during the ingress to the stadium (0.125 m^2 per person) and during overcrowding eventually leading to a disaster (0.1 m^2 per person) [14]. Thus, even an uncomfortably small personal space is tolerated for a while if there is a good reason behind it.

3   FITTING BODY ELLIPSES IN A LIFT CAR

The problem of finding the maximum number of passengers that a lift can accommodate is modelled as a 2-dimensional packing problem which aims to determine the maximum number of body ellipses that can be packed within a rectangle. *The Ellipse Packing Problem* (*EPP*) is solved by applying an iterative algorithm, where, in each iteration, first *the Ellipse Feasibility Problem* (*EFP*) checks whether all the ellipses fit within the rectangle and do not cross their boundaries, then the number of ellipses is increased by one and the next iteration is carried out. If a feasible solution is not found in the current iteration, the algorithm terminates and the optimal solution to the EPP is the last feasible set of ellipses.

The EFP is formulated as a nonlinear programming problem where its optimal value equals zero if it exists. Let E denote the set of ellipses and W the set of walls of the lift car. Define $EEO(e, f)$ to be the overlapping area of ellipses e and f, and $WEO(e, w)$ to be the overlapping area of ellipse e and wall w. With this notation, the EFP can be written as follows:

$$\min \sum_{e,f \in E | e \neq f} EEO(e, f) + \sum_{e \in E, w \in W} WEO(e, w) \tag{1}$$

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[1]These body ellipses are calculated from the 95th percentile shoulder breadth (bideltoid) and the larger one of chest and abdominal depth without any additional space around.

The problem involves three decision variables for each ellipse: one for rotation, which determines the angle between the ellipse major axis and x-axis, and two for translation, which determine the x- and y-coordinate of the ellipse centre point. Successive quadratic programming is applied to solve the problem. The overlapping areas are calculated by the method presented in [15].

The numerical experiments consider general-purpose lifts of ISO 4190-1 [16], whose rated loads (*RL*), widths (*B*) and depths (*D*) are given in Table 2. The table also shows the *Passenger Capacity* (*PC*), the internal *Car Area* (*CA*), the *Car Load Factor* (*CLF*), and the *Area Per Passenger* (*APP*), which are derived as follows by assuming that a passenger weighs 75 kg on average and denoting the number of passengers by *P*:

$$PC = RL/75 \,, \tag{2}$$

$$CA = B \times D \,, \tag{3}$$

$$CLF = P/PC \times 100\% \,, \tag{4}$$

$$APP = \frac{CA}{CLF \times PC} \,. \tag{5}$$

Table 2. Car dimensions, passenger capacities, car areas calculated from the ISO 4190-1 dimensions and the average areas per passenger with 100% car load factor

RL [kg] ISO 4190-1	B [mm] ISO 4190-1	D [mm] ISO 4190-1	PC [N] EN 81-1	CA [m²] ISO 4190-1	APP [m²]
800	1350	1400	10	1.89	0.189
1000	1600	1400	13	2.24	0.172
1275	2000	1400	17	2.8	0.165
1600	2100	1600	21	3.36	0.160
1800	2350	1600	24	3.76	0.157
2000	2350	1700	26	3.995	0.154

First, the largest body ellipse dimensions that still fit in a 2000 kg lift are sought for a fixed number of identical passengers. The number of passengers is varied so that the corresponding car load factor varies from 50 to 100% in 10% steps. The aspect ratio of the ellipses is set to 1.82, which is the average ratio of the maximum body breadth to the maximum body depth for the 5th, 50th, and 95th percentile points for men [7]. Table 3 presents the dimensions of the largest ellipses found for each car load factor and their areas. The area utilization percentage gives the total area of all the ellipses divided by the car area, the maximum utilization being equal to 84.6%. Since the 2000 kg lift has the smallest area per passenger, these results show that all lifts of Table 2 can be fully loaded with identical passengers if their body ellipses occupy at most 0.130 m².

Next, the maximum number of passengers that fit in the lifts of Table 2 is determined by considering several compositions of passenger groups with different body sizes. The dimensions of each passenger group are given in Table 4. The first passenger group consists of identical males with the Fruin body ellipse. The second passenger group models identical females and is obtained from the 95th percentile point of the clearance dimensions [7] with an additional 15 mm width and

125 mm depth (to obtain good round values). The last two passenger groups represent males and females with body ellipse sizes drawn randomly. The widths of these ellipses follow the normal distributions of the male and female maximum body breadths with the averages of 530 mm and 420 mm, respectively [7]. The aspect ratios between the body width and depth are 1.82 for males and 1.53 for females. The width and depth are also increased by 20 mm to allow some space for clothing, which is twice the recommended 10 mm correction for indoor clothing but half of the recommended 40 mm correction for heavy outdoor clothing [7]. This assumption models the situation where passengers are under pressure of packing the lift and smaller-than-usual personal space can be tolerated.

Table 3. The largest possible ellipse sizes for given car load factors in a 2000 kg lift

CLF [%]	Passengers [N]	Ellipse Width [mm]	Ellipse Depth [mm]	Ellipse area [m^2]	Area utilization [%]
50	13	776	426.4	0.266	84.6
60	15	714	392.3	0.220	82.6
70	18	655	359.9	0.185	83.3
80	20	619	340.1	0.165	82.6
90	23	580	318.7	0.145	83.5
100	26	549	301.6	0.130	84.6

Table 4. Axis lengths and average area of body ellipses for each passenger group

Passenger group	Ellipse Width [mm]	Ellipse Depth [mm]	Ellipse Area [m^2]
Male-95	600	450	0.212
Female-95	500	450	0.177
Male-Gaussian	$\sim N(530, 30) + 20$	Width / 1.82 + 20	0.130
Female-Gaussian	$\sim N(420, 40) + 20$	Width / 1.53 + 20	0.099

Four scenarios combine the above passenger groups differently. In *Male-95* and *Female-95* scenarios, all passengers are identical 95th percentile males and females from the corresponding passenger groups. The *Mixed-95* scenario consists of passengers from the Male-95 and Female-95 groups so that there is an equal number of males and females. In the *Mixed-Gaussian* scenario, male and female passengers are randomly selected from the respective normal distributions with a passenger having an equal probability of being male or female. The scenarios are solved for the lifts specified in Table 2. The Mixed-Gaussian scenario is solved ten times with redrawn random samples for the ellipse widths and average values are reported instead of individual runs. Figure 1 shows the distributions for the male and female ellipse widths and individual random samples drawn for a 2000 kg lift.

Figure 2 shows the maximum number of passengers that fits in the lifts in the different scenarios. From the figure one can observe that the maximum number of passengers that can be loaded follows a linear trend with dependency on the rated load and the body ellipse size. The lifts can accommodate full load only in the Mixed-Gaussian scenario, i.e. when the ellipse widths are drawn randomly from the normal distributions and passengers are males or females with equal probability.
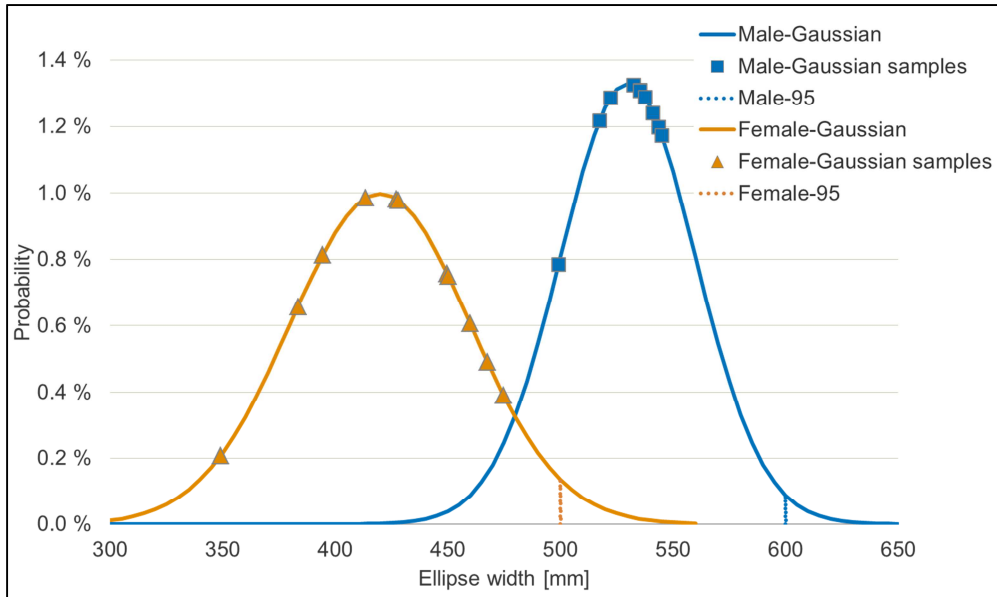
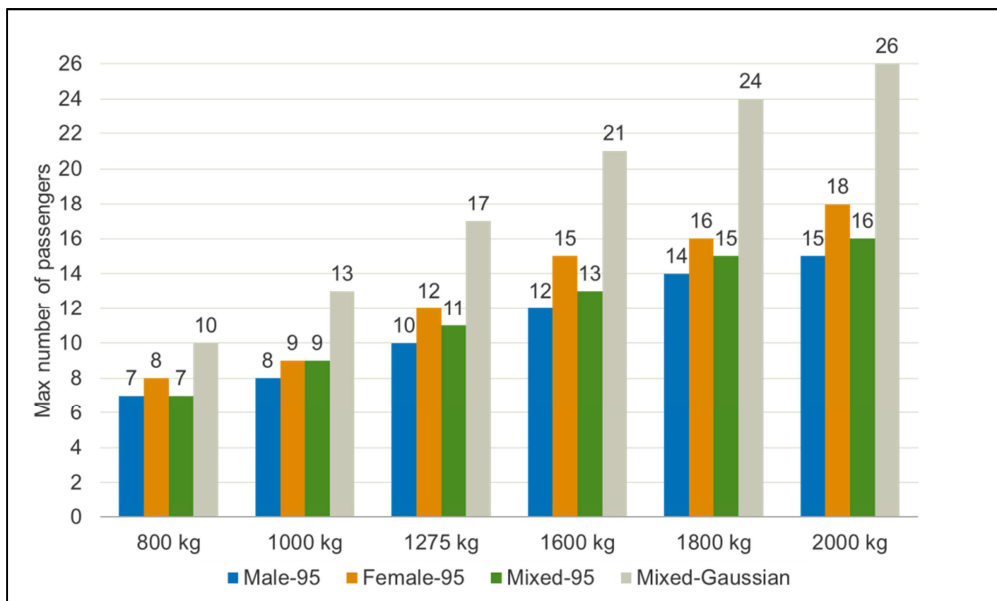**Figure 1. Mixed-Gaussian and 95th percentile ellipse widths**

Figure 2. Maximum number of passengers that fit in the lifts

Table 5 gives the maximum car load factors for the scenarios. In the Male-95 scenario, the car load factor is as low as 57.1% for the 1600 kg lift. It is also worthwhile noticing that the maximum number of passengers in this scenario is always notably less than the area-based passenger capacity [4, 9] although the body ellipses have the same area. The difference occurs because the car area is not fully utilized. In the Mixed-Gaussian scenario, cars can be fully loaded. Table 6 presents the average available areas per passenger. The scenarios consisting of 95th percentile males and females have the average area per passenger in the range of comfortable densities. However, the available areas with the Mixed-Gaussian passengers are well below 0.2 m^2 per passenger but still clearly above the average body ellipse sizes 0.130 m^2 of men and 0.099 m^2 of women.
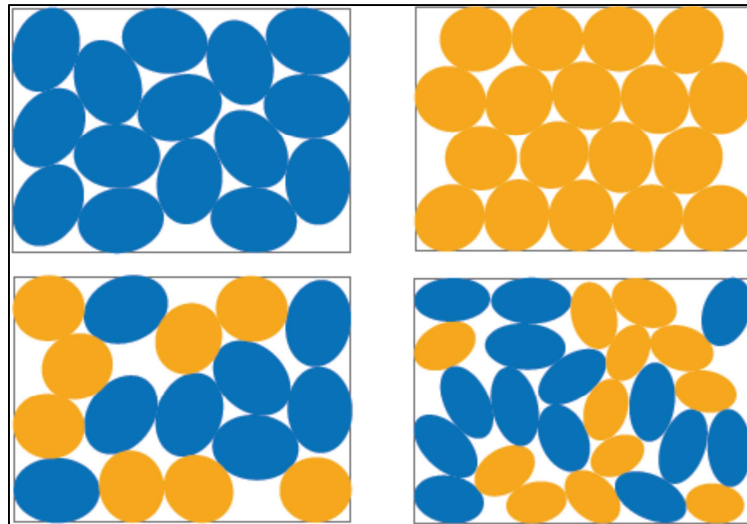
Figure 3: Solutions with different body ellipse scenarios for the 2000 kg lift. Top left: 15 Male-95 ellipses; top right: 18 Female-95 ellipses; bottom left: 8 Male-95 ellipses and 8 Female-95 ellipses; bottom right: 14 Male-Gaussian ellipses and 12 Female-Gaussian ellipses.

Table 5: Car load factors based on the maximum number of passengers

Scenario	Car Load Factor [%]					
	800 kg	**1000 kg**	**1275 kg**	**1600 kg**	**1800 kg**	**2000 kg**
Male-95	70.0	61.5	58.8	57.1	58.3	57.7
Female-95	90.0	76.9	76.5	71.4	70.8	73.1
Mixed-95	80.0	69.2	70.6	66.7	62.5	61.5
Mixed-Gaussian	100.0	100.0	100.0	100.0	100.0	100.0

Table 6: Available area per passenger based on the maximum number of passengers

Scenario	Area per passenger [m^2]					
	800 kg	**1000 kg**	**1275 kg**	**1600 kg**	**1800 kg**	**2000 kg**
Male-95	0.270	0.280	0.280	0.280	0.269	0.266
Female-95	0.270	0.249	0.233	0.240	0.235	0.222
Mixed-95	0.270	0.249	0.255	0.258	0.251	0.250
Mixed-Gaussian	0.189	0.172	0.165	0.160	0.157	0.154

4   LEVEL OF SERVICE IN A LIFT CAR

Traditionally, the lift group handling capacity is defined with 80% average car load of the load-based passenger capacity, which implicitly assumes that sometimes the lifts are occupied up to 100% of their capacity. As shown, 100% loading is physically possible when considering a realistic distribution of human body dimensions and mixture of men and women. Thus, the assumption of 100% loading in theoretical calculations and simulations remains valid.

In practice, only up to 76% loading has been observed [13], which is (probably) caused by passengers' desire for personal space. The traditional way of conducting lift traffic design calculations and simulations does not take into account the area occupied by a passenger but that is easily overcome by considering area per passenger as a new design metric.

The value of area per passenger is calculated using the average car load factor as in Eq. 5, which defines the number of passengers for the up-peak equations and is readily available as a simulation statistic [17]. Then, the area per passenger is compared with the Fruin Level of Service (LOS) ranges for queuing areas, of which LOS E is given as an example for lift occupancy [5]. As shown in Table 7, the lower limit of LOS E occupancy (0.2 m^2 per passenger) corresponds to 80% (or greater) car load factor for rated loads up to 1600 kg. For 1800 kg or 2000 kg lifts, 77-78% car load factor result in area per passenger within LOS E lower limit. Thus, the usual way of defining maximum handling capacity with the average car load factor 80% is in line with LOS E. On the other hand, occupancy of 0.3 m^2 per passenger on the upper limit of LOS E occurs with car load factors between 55% and 60%, which can be considered as a good target value for comfortable travel.

Table 7. Area per passenger, LOS with increasing car load factor and LOS ranges [5]. APP calculated using load-based passenger capacity (Eq. 2) and car areas as in Table 2.

CLF [%]	Area per passenger [m^2] and LOS						LOS	APP [m^2]
	800 kg	1000 kg	1275 kg	1600 kg	1800 kg	2000 kg		
10	1.890	1.723	1.647	1.600	1.567	1.537	A	≥1.2
20	0.945	0.862	0.824	0.800	0.783	0.768	B	0.9-1.2
40	0.473	0.431	0.412	0.400	0.392	0.384	C	0.7-0.9
60	0.315	0.287	0.275	0.267	0.261	0.256	D	0.3-0.7
80	0.236	0.215	0.206	0.200	0.196	0.192	E	0.2-0.3
100	0.189	0.172	0.165	0.160	0.157	0.154	F	< 0.2

The use of LOS does not change the traditional way of conducting lift traffic calculations and simulations. Thus, the definition of the passenger capacity remains load-based according to the applicable local standard. LOS involves only the calculation of the area per passenger and its classification as an extra work using car load factor and car area. However, the area per passenger is a rather abstract concept, but it could be visualized by schematic drawings [5] or by 3D visualization of traffic simulation [18].

5   DISCUSSION

The load-based passenger capacity accompanied with the area per passenger as a service quality metric has many advantages over the area-based capacity. Firstly, new lift traffic designs with the area-based passenger capacity are not in line with the old ones conducted with the load-based passenger capacity since area-based passenger capacity is 58-90% of load-based passenger capacity [4]. Also the lift group handling capacity decreases by the same ratio just because of the definition of passenger capacity changes. When keeping the traditional load-based passenger capacity intact, new designs can be compared directly to old ones while the area per passenger brings additional information about the suitability of the design.

Since passenger capacity is the determinant of the traffic design calculations, the assumed body ellipse area affects directly the results of the analysis. Therefore, the occupancy area should represent an average user of the target building type, geographical area, and culture. The definition of area-based passenger capacity is based on the occupancy area 0.21 m^2 per passenger weighing 75 kg [4, 9], which is the area of the Fruin body ellipse [5]. However, the Fruin body ellipse was derived for 95th percentile male dimensions, which corresponds to about 90 kg man and is not in line with the previous assumption. In addition, the body ellipse contains 0.06 m^2 additional space around the body. Thus, the area-based passenger capacity hides the assumptions behind it without proper documentation, which is not the case for the load-based passenger capacity. In addition, area per passenger does not depend on the choice of average passenger occupancy area, and, therefore, it is independent of culture, geographical area, and building type.

Since lift traffic calculations and simulations are based on mathematical theories, complex relationships, and many technical parameters, the rationale and effect of area-based passenger capacity remains hidden from and incomprehensible to the decision maker. Then, the designer is responsible for the validity of the design assumptions and the decision maker is (probably) neither able to challenge them nor provide insights of the target occupants. If the lift traffic analysis shows the area per passenger as well as the LOS classification, the decision maker and the designer may enter the debate whether the proposed solution is adequate for the building under consideration. Thus, the decision maker is able to make an informed decision based on his/her assessment on all aspects of the lift passenger service.

The standards allow some variation in car dimensions, which results in different internal car areas and therefore area-based passenger capacities. In addition, the lift manufacturers may have their own dimensions within the limits of the standards. Thus, the designer cannot know the true dimensions of the car before the lift supplier is chosen for the project, and therefore, the calculations with area-based passenger capacity are not necessarily correct. Furthermore, the car area available to the passengers may be further reduced from the standard due to car shape, hand rails, and decoration, the effect of which may or may not be known to the designer during the building design phase. Thus, even a small change in the available car area may change the area-based passenger capacity and, therefore, also invalidate the conducted analysis. The use of load-based passenger capacity and area per passenger does not completely eliminate the effect of non-unique car areas. However, the change in car area does not require a re-run of the whole analysis, only re-evaluation of area per passenger is needed. Since the range of LOS E is quite wide, a small change in the car area does not necessarily imply a notable change in the area per passenger.

6   CONCLUSION

This article studied human body sizes and how they could be taken into account in lift traffic design. The motivation for this study arises from the two definitions of passenger capacity, which is the maximum number of passengers a lift car can accommodate. Current lift safety standards define the passenger capacity by dividing lift rated load by the average passenger weight, which is in Europe 75 kg. In an alternative approach, the maximum allowed car area is divided by the 0.21 m^2 body ellipse area of a passenger weighing 75 kg. Of these two definitions, the area-based gives much smaller passenger capacity than the load-based, which creates unnecessary confusion among the practitioners.

When studying the maximum loading of lifts, it was found that the standard-sized lifts can be loaded up to 100% of the load-based passenger capacity. Full load was achieved when lifts with different rated loads were packed with body ellipses drawn randomly from body dimension distributions of men and women. This shows that the maximum car occupancy in lift traffic design should be 100% of the load-based passenger capacity. Thus, the real-world observation that a lift is

not loaded up to 100% must be the consequence of human behaviour and preferences. Therefore, the available space for passengers should not be treated as a matter of capacity.

Since personal space in a lift is an important factor in comfortable travelling, it should be considered explicitly in lift traffic design. The Level of Service concept developed by Fruin can be applied to lifts since the design calculations and simulations have readily available the average number of passengers in the lift. Then, it is possible to calculate the average area per passenger and classify it according to the existing Level of Service definitions for queuing areas. Fruin recommended lifts to be the only application of LOS E with 0.2-0.3 m^2 area per passenger. Coincidental or not, 80% average car load, which has been used for a long time to define the maximum handling capacity of a lift group, corresponds to the LOS E for lifts up to 1600 kg rated load. Therefore, the use of 80% car load factor in lift traffic design seems to be a valid approach. The consideration of exact area per passenger offers a way of defining target car load factor for large lifts of 1800 kg or greater, or a requirement for a more spacious solution than provided with 80% car load factor.

The advantage of using LOS and area per passenger over the area-based passenger capacity is based on its independence of building type, geographical area, culture, and differences in body sizes. Therefore, lift traffic design should be carried out in the traditional way by using the load-based passenger capacity to determine service quantity and area per passenger as an additional selection criterion for service quality. This provides a straightforward way to settle the conflict between the load- and area-based passenger capacities and keep the future traffic designs in line with the old ones.

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