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FOREWORD

It is with great pleasure that we present the proceedings of the 13th Symposium on Lift and Escalator Technologies, 21-22 September 2022, organised by The Lift and Escalator Symposium Educational Trust. In 2020 and 2021 the Covid 19 pandemic necessitated the Symposium to take place online. We are delighted to be back in Northampton for a full in-person conference.

The objective of The Lift and Escalator Symposium Educational Trust is to advance education in lifts, escalators and related technologies. The Trust is a Registered Charity No: 1170947 and is supported by The University of Northampton, The Chartered Institution of Building Services Engineers (CIBSE) and The Lift and Escalator Industry Association (LEIA).

Proceedings from the full conference series (since 2011) are available to download from www.liftsymposium.org. The proceedings are indexed in Scopus as “Symposium on Lift and Escalator Technologies”, starting from the 2015 Symposium. Scopus is the world’s largest abstract and citation database of peer-reviewed literature (scientific journals, books and conference proceedings), see https://blog.scopus.com/about.

The Lift Engineering programme offered at The University of Northampton includes postgraduate courses at MSc/ MPhil/ PhD levels that involve the 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.

LEIA is the UK trade association and advisory body for the lift and escalator industry with a membership covering some 95% of the lift and escalator industry. LEIA members supply passenger and goods/service lifts, stairlifts, homelifts, lifting platforms, escalators, passenger conveyors and a range of component parts for such products. LEIA members undertake the maintenance and modernisation of more than 250,000 products falling within the scope of the Association. LEIA provides advice on health, safety and standards matters, promotes education and training, especially through its distinctive distance learning programme.

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 postgraduate students.

The papers are listed alphabetically by first author surname. The requirement was to prepare an extended abstract, but full papers were accepted where the speakers 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. The proceedings also include an invited book review of “People Flow in Buildings”.

Professor Stefan Kaczmarczyk, and Dr Richard Peters
Co-Chairs and Proceeding Editors

CONTENTS

Enhancing the I-S-P Method (Inverse Stops-Passengers) Using the Monte Carlo Simulation Method

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Keywords: Monte Carlo Simulation, elevator, lift, passengers, stops, ISP Method.

Abstract. Previous research has developed a method to infer the number of passengers that the lift car is carrying based on the number of stops that it makes in the up-direction or the down-direction (1992). The method was denoted as the I-S-P method (or the Inverse Stops-Passengers method). The application of the method was found to be sensitive to the prevailing mix of traffic in the building (e.g., incoming, outgoing or lunchtime). Developing those equations analytically becomes mathematically complex.

This paper will use the Monte Carlo simulation method to numerically develop the ISP relationship under any mix of traffic (i.e., by using the percentage of incoming traffic, outgoing traffic and inter-floor traffic), without the need to resort to deriving analytical equations. The ISP method gives an estimate of the passenger traffic intensity based on a very basic dispatching control system.

The main advantage of such an enhanced tool is that it can be used in real time to infer the number of passengers inside the car by simply monitoring the stops in any one of the two directions and under any type of traffic.

1 INTRODUCTION

Once a lift system has been installed, the need might arise for checking the performance of the lifts, or, if the lifts have been in service long enough, to refurbish the lift system. In order to do this, the actual number of passengers using the lift system in different traffic conditions and the profiles of the traffic patterns have to be available. These could either be assessed or surveyed.

Assessment techniques rely on using a percentage of the building population [1,2]. This method expresses the expected worst five minute up-peak demand as a percentage of the building population, with different figures for different types of buildings.

Manual surveys on the other hand give the size of the traffic and the profile against time but are limited by the length of time for which human observers can conduct them, unless more human resources are deployed. A good overview of surveys can be found in [3]. From a practical point of view, manual surveys are not usually conducted for more than 2 - 4 hours a day, and for 2 - 3 days per building. Another disadvantage is that manual surveys can only be conducted at one floor, (usually the main terminal), and thus do not take into consideration other heavy traffic floors (unless more human resources are employed). If a complete performance analysis is needed, at least one observer is needed on every floor and in every car [4].

Other research has been carried out in order to analytically attempt to extract the full details of passenger movements in the building by logging the landing calls and the car calls [5,6]. This method assumes that the landing call and car call data is fully available to the algorithm.

Previous work has attempted to allow the inference of the number of passengers boarding the lift car in either direction by counting the number of stops in that direction and applying it to a lookup table (denoted as the ISP table). The entries in the table were derived analytically. This was only done for pure up traffic (or incoming traffic) [7, 8, 9, 10]. Extending the equation derivation for the more complex cases of mixed traffic conditions and inter-floor traffic becomes very complicated.

It is worth noting that the number of elevator stops/starts depends not only on the passenger traffic and the traffic mix, but also the control system [1].

This paper attempts to extend this table to general traffic conditions by using a numerical method (as opposed to the original analytical method) called the Monte Carlo simulation method. The Monte Carlo simulation method has been used recently in the area of lift traffic engineering. It was used to find the value of the round-trip time under incoming traffic conditions [11] and then under general traffic conditions [12]. It was also used to find the value of the average travelling time [13]. In some of the more recent papers, it was used to evaluate the round-trip time for hypothetical traffic systems [14, 15, 16] and even under destination group control [17]. Comparisons have been carried out between the value of the round-trip time resulting from the Monte Carlo simulation method and existing techniques, whereby the Monte Carlo simulation method was also used as an extension to existing methods [18]. Special emphasis was also given to the effect of the adopted dispatcher [18].

Section 2 presents definitions of the stop and the procedure for generating the tables using the Monte Carlo simulation method. Section 3 shows the resultant tables under morning peak traffic conditions and lunchtime traffic conditions. An example of the application of the method to ten consecutive round trips is presented in section 4. Section 5 draws conclusions and suggests the most relevant piece of further works.

2 DEFINITIONS AND PROCEDURE

The code to generate the ISP tables was implemented in MATLAB. The building number of floors (entrance floors with their respective entrance bias and occupant floors with their relative occupant populations) are entered into the software, as well as the traffic mix (incoming: outgoing: interfloor). All this information is used to generate an origin-destination matrix (OD matrix) and then a probability density function and a cumulative distribution function for the passenger origin-destination pairs. More details can be found in [19]. The number of passengers served in each round trip (P) is entered in order to generate the ISP array. The number of passengers P was selected as equal to the rated car capacity (although in future work this will be varied to cater for different arrival rates.

Th code was repeated for a large number of trials (e.g., 100 000 trials). The term trial is a Monte Carlo simulation expression. In this case, each trial represents one full round trip of the lift, during which the rated number of passengers (P) is generated in accordance with the origin-destination matrix. The number of up travelling passengers was extracted as well as the number of up stops. The same was applied to the down direction. At the end of the 100 000 trials, the cases for the same number of stops were aggregated together in each direction and the average of all the corresponding number of passengers was calculated. These entries were placed in the two ISP tables (one for the up direction and one for the down direction).

The tables were developed for two mixes of traffic:

1. Morning peak (85% incoming traffic; 10% outgoing traffic; and 5% interfloor traffic).
2. Lunchtime peak (45% incoming traffic; 45% outgoing traffic; 10% interfloor traffic).

Another critical factor that was fixed was the number of passengers generated in one round trip. This represents the traffic intensity. In the example used in this case, it was set to 13 passengers.

Prior to developing the software to generate the ISP tables, it was necessary to define what constitutes an up stop and a down stop. A stop is classified as an up stop in either of the following two cases

1. If the lift car is stopping to pick up one or more passengers travelling up the building.
2. If the lift car is stopping to drop off one or more passengers travelling up the building

A stop is classified as a down stop in either of the following two cases

1. If the lift car is stopping to pick up one or more passengers travelling down the building.
2. If the lift car is stopping to drop off one or more passengers travelling down the building

There are obviously cases where a *physical* stop could represent both an up stop and a down stop (e.g., a lift car that is travelling in the up direction to drop off an up travelling passenger and to pick an up or a down travelling passenger). This could be referred to as a coincidental stop and was counted twice: once as an up stop and once as a down stop. The MATLAB software can detect that this is a coincidental stop.

Later in this paper, the use of an accelerometer that is placed on the floor of the lift car is presented as a simple and non-intrusive tool to detect the physical stoppage of the lift. However, the accelerometer inside the lift car will not be able to detect whether the stop described above is a coincidental stop or not.

3 RESULTANT ISP TABLES FOR A SAMPLE BUILDING

The software was written in MATLAB, for the following sample building:

1. The building has a total of 10 floors (2 entrance floors and 8 occupant floors). The entrance bias was set to 0.3 for the lower entrance and 0.7 for the upper entrance.
2. The number of passengers generated in each round trip was set to P=13 passengers. The number of passengers P in each round trip is a representation of the traffic intensity.
3. The number of trials was set to 100 000 trials.

The four resultant ISP tables are shown in

Table **1** and

Table **2** for the morning peak and the lunchtime peak, respectively. For the traffic mix, two tables were generated: one for the up direction and the other for the down direction. Improbable cases (cases which have not occurred during the 100 000 round trips) are highlighted in orange. Impossible cases (e.g., one passenger generating only one stop) are highlighted in yellow. It is worth noting that the kinematics and door timings are irrelevant to these tables and would not have any effect on their contents.

Table 1: Morning Peak ISP Table generated using MCS for P=13 passengers.

Morning Peak (85%:10%:5%)	Up ISP Table										
	Stops	0	1	2	3	4	5	6	7	8	9	10
	Passengers	improbable	impossible	improbable	improbable	5	6.8333	8.4812	9.7798	11.1658	12.2563	13
	Down ISP Table											
	Stops	0	1	2	3	4	5	6	7	8	9	10
	Passengers	0	impossible	1.0415	2	2.3746	3.163	4.0882	5.0822	6.1225	7.45	improbable

Table 2: Lunchtime Peak ISP Table generated using MCS for P=13 passengers.

Lunchtime Peak (45%:45%:10%)	Up ISP Table										
	Stops	0	1	2	3	4	5	6	7	8	9	10
	Passengers	0	impossible	1.3153	2.1511	3.2291	4.3923	5.5713	6.8272	8.2874	9.5912	11.1897
	Down ISP Table											
	Stops	0	1	2	3	4	5	6	7	8	9	10
	Passengers	0	impossible	1.3333	2.1789	3.252	4.4035	5.5681	6.8269	8.2872	9.6075	11.213

4 APPLICATION OF THE METHOD

The aim of applying this method is to place an accelerometer inside the lift car and log the number of stops in the up direction and the number of stops in the down direction in each round trip. The method would use the produced tables (shown in the previous section) to infer the number of up passengers in each round trip (based on the number of stops in the up direction) and to infer the number of down passengers in each round trip (based on the number of stops in the down direction).

An example that shows how this method has been applied to 10 consecutive round trips is shown in Figure 1. It shows the actual number of passengers in each round trip against the inferred number of passengers for each round trip. Generally, the numbers agree reasonably well. However, this is due to the fact that the system has exact knowledge of the mix and intensity of traffic.

Figure 1 was generated during simulation. Further work will include actual site data surveyed.

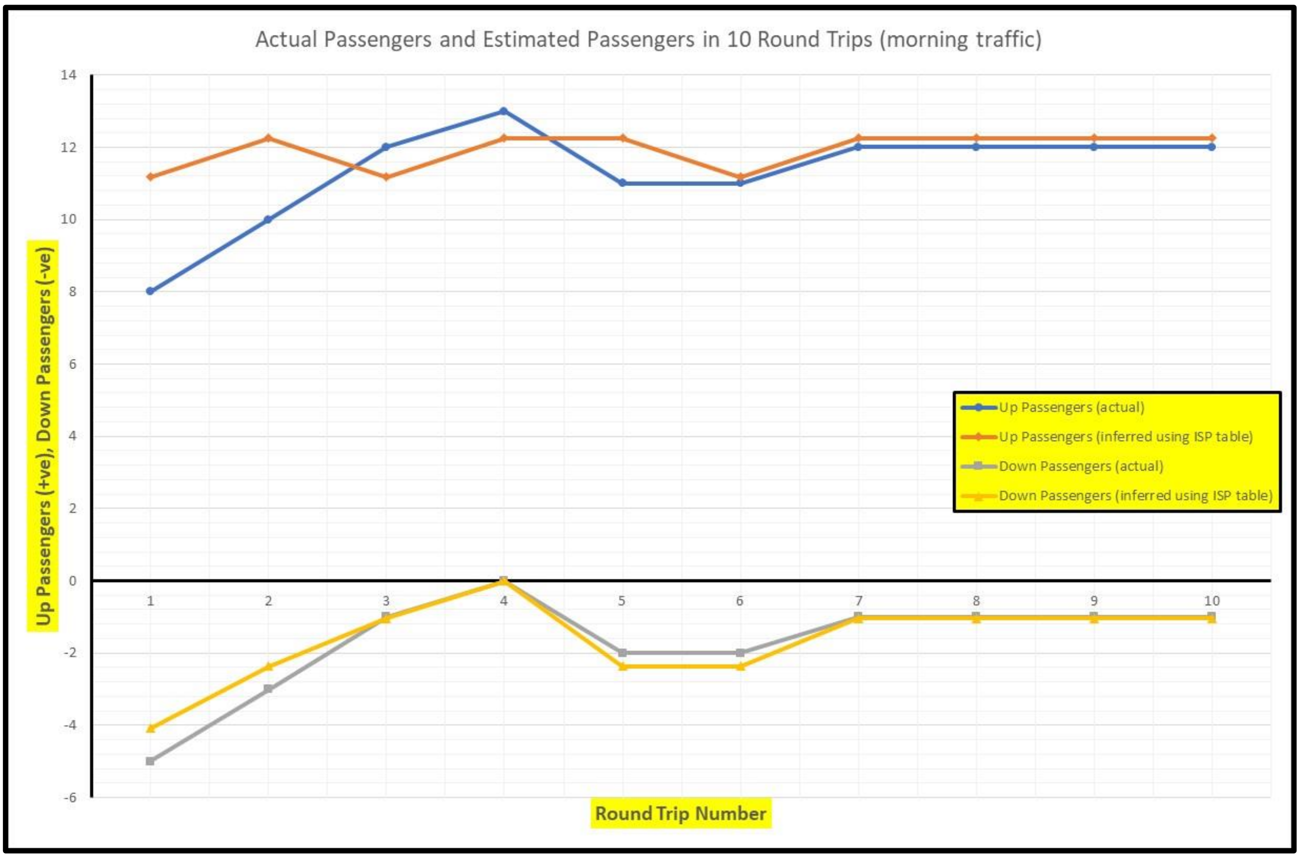

Figure 1 Actual passengers and inferred passengers for 10 round trips.

Another possible application of the method is to have it built within a dispatcher that is linked to the lift controller, that already knows about the stops.

In real life applications, only an estimate of the traffic mix and intensity would be available to the application and the accuracy of the method would suffer.

An alternative would be to develop a “Robust Control” method, where the ISP tables are generated without assuming exact knowledge of the traffic mix and intensity. This will however lead to lower accuracy but will be better than using the tables that assume exact knowledge when the assumption is incorrect. Hence this method would be termed a “Robust” method.

This would be the aim of the application. More details about this are contained in the “Future Work” section at the end of this paper.

5 CONCLUSIONS

The ISP method was developed in order to derive suitable equations that allow the user to infer the number of passengers using the lift in any one direction from the number of stops.

In this paper, the ISP method has been further extended, using the Monte Carlo simulation method, to be applicable to any traffic mix and implemented in order to generate lookup tables that will allow users to infer (a best estimate of) the number of passengers travelling in the lift car in a specific direction based on the number of stops that the car makes in that direction.

The main disadvantage of the method, however, is that it does require an estimate of the intensity of traffic prevailing in the building at the time of the survey, as well as the mix of traffic being split into incoming, outgoing and inter-floor percentages. In cases where this information is not available, it is possible to resort to robust control techniques and develop an ISP table that is independent of the traffic intensity and traffic mix, but which will yield less accurate results.

Although there are other methods that can be used to infer the number of stops and the number of passengers using the lift car, they mainly rely on hardware (e.g., light ray). The main purpose of the ISP method is to simply use an accelerometer inside the lift car to infer the number of passengers.

6 FURTHER WORK

Further work will concentrate on assessing the loss in accuracy that results from resorting to the robust method, as opposed to the error that will result from using the tables that assume exact knowledge and applied under incorrect traffic conditions.

Moreover, for the method to be practical, it must not assume any prior knowledge of the intensity of the prevailing traffic in the building or the mix of traffic. So, another aim of future work would be to develop a method that can be used to estimate the intensity of traffic in the building and the mix of traffic. The overall method would operate by first estimating the intensity of traffic and the traffic mix in the building and then generating and applying the corresponding ISP tables to estimate the exact traffic patterns in the building.

A further study could be addressed to discover the traffic intensities where the number of stops/starts begins to saturate and how much the saturation depends on the number of floors and the car capacity.

Improving the accuracy of the method could also be achieved by considering multiple days in the analysis (e.g., collecting a month’s worth of data and then taking the average of the number of up/down stops in each 5-minute period).

REFERENCES

[1] Barney G C and Al-Sharif L. Elevator Traffic Handbook: Theory and Practice. 2nd Edition. Routledge, Abingdon-on-Thames, United Kingdom. 2016.

[2] CIBSE (Chartered Institute of Building Services Engineers). CIBSE Guide D: Transportation systems in buildings. 2020. Published by the Chartered Institute of Building Services Engineers (Balham, London, United Kingdom), Sixth Edition.

[3] Peters R D and Evans E. Measuring and Simulating Elevator Passengers in Existing Buildings. *Elevator Technology 17*, proceedings of Elevcon 2008, Thessaloniki, Greece, pp 289-300.

[4] Beebe J R. Lift Management. Ph.D. Thesis. Control Systems Centre, The University of Manchester, 1980.

[5] Kuusinen J M, Sorsa J and Siikonen M L. The elevator trip origin-destination matrix estimation problem. *Transportation Science*, 2015; 49(3): 1-18.

[6] Kuusinen J M and Malapert A. The effect of randomisation on constraint-based estimation of elevator trip origin-destination matrices. *4th Symposium on Lift and Escalator Technologies*, University of Northampton, 25th to 26th September 2014.

[7] Al-Sharif L R and Barney G C. *The Inverse S-P Method: Deriving Lift Traffic Patterns from Monitored Data.* Control Systems Centre, University of Manchester, Report Number: 745, 18th September 1991.

[8] Al-Sharif L R and Barney G C. The Application of the Inverse *S-P* Method in Deriving Up Traffic Patterns. Control Systems Centre, The University of Manchester, Report Number 746, 18th September 1911.

[9] Al-Sharif L R and Barney G C. The use of moving averages in filtering lift traffic patterns. Control System Centre, The University of Manchester, Report Number 747, 18th September 1991.

[10] Al-Sharif L. *Predictive Methods in Lift Traffic Analysis*. The University of Manchester, 1992.

[11] Al-Sharif L, Aldahiyat H M and Alkurdi L M. The use of Monte Carlo simulation in evaluating the elevator round trip time under up-peak traffic conditions and conventional group control. Building Services Engineering Research and Technology 2012; 33(3): 319–338. doi:10.1177/0143624411414837.

[12] Al-Sharif L and Abu Alqumsan A M. An Integrated Framework for Elevator Traffic Design under General Traffic Conditions Using Origin Destination Matrices, Virtual Interval and the Monte Carlo Simulation Method. Building Services Engineering Research and Technology 2015; 36(6): 728-750.

[13] Al-Sharif L, Abdel Aal O F and Abu Alqumsan A M. Evaluating the Elevator Passenger Average Travelling Time under Incoming Traffic Conditions using Analytical Formulae and the Monte Carlo Method. Elevator World 2013; 61(6): 110-123. June 2013.

[14] So A, Al-Sharif L and Hammoudeh A. Traffic analysis of a simplified two-dimensional elevator system. Building Services Engineering Research and Technology. 2015; 36(5): 567-579. doi:10.1177/0143624414568728.

[15] So A, Al-Sharif L and Hammoudeh A. Concept design and derivation of the round trip time for a general two-dimensional elevator traffic system. Journal of Building Engineering 2016; 5(2016): 165-177.

[16] So A, Al-Sharif L and Hammoudeh A T. Analysis of possible two dimensional elevator traffic systems in large buildings. Elevator Technology 20 2014; 20:51-61. Paris, France, July 2014.

[17] Al-Sharif L and Peters R D. Using the Monte Carlo Simulation to Evaluate the Round-Trip Time under Destination Group Control. 9th Symposium on Lift & Escalator Technologies, Northampton, United Kingdom. September 2018.

[18] Appleby M and Peters R D. The Round-Trip Time Simulation: Monte Carlo Implementation and Consistency with Other Techniques. *Proceedings of the 11th Symposium on Lift and Escalator Technologies (online)*. 2020.

[19] Al-Sharif L. A Universal Methodology for Generating Elevator Passenger Origin-Destination Pairs for Calculation and Simulation. In the Book (chapter 6): Smart Cities-Their Framework and Applications, published by IntechOpen, 25th September 2020.

BIOGRAPHICAL DETAILS

Lutfi Al-Sharif is currently the Dean of Engineering Technology and Professor of Electrical Engineering at Al-Hussein Technical University in Amman/Jordan and jointly Professor of Building Transportation Systems at the Department of Mechatronics Engineering, The University of Jordan. He received his Ph.D. in elevator traffic analysis in 1992 from the University of Manchester, U.K. He worked for 10 years for London Underground, London, United Kingdom in elevators and escalators. He has over 50 papers published in peer reviewed journals and conferences in vertical transportation systems, is co-inventor of four patents and co-author of the 2nd edition of the Elevator Traffic Handbook, and author of the “indoor transportation” chapter in the Elsevier Encyclopedia of Transportation.

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Impact of the Load-Area Bypass Feature on Passenger Service Quality

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Keywords: bypass feature, floor area occupancy, unnecessary stop.

Abstract. A lift stop is unnecessary if a lift stops to serve a call, but no passengers enter or exit the lift. There are many reasons for such a situation. For example, a passenger accidentally makes a call to the wrong floor, or a lift stops to pick up passengers, but no one enters the lift car since the waiting passengers consider the car full. In this paper the focus is only on the latter mentioned case. Traditionally, such unnecessary stops are reduced by using a load bypass feature. In this feature, a lift starts bypassing registered landing calls when the car is loaded over a configurable limit, called bypass load. When there are only passengers travelling, the load bypass feature works well in eliminating unnecessary stops. Nevertheless, when passengers transport light objects with them such as luggage or shopping carts, the floor area of a lift car may be fully occupied but the load is still below the bypass load limit and as a result, unnecessary stops may occur. If information about floor area usage of a lift car is available, i.e., what is the occupied percentage of the lift floor area by passengers and their belongings, then unnecessary stops will be better prevented. This paper studies how the number of unnecessary stops is dependent on different factors such as traffic intensity and pattern, and how much passenger service quality is improved in conventional control buildings when the floor occupancy information of lifts is used, in addition to load, in the bypass feature by analysing simulation results from a large set of hypothetical instances. The set is formed by varying traffic intensity, traffic pattern, number of objects transported and their sizes, lift group size, as well as the floor occupancy threshold and measurement error.

1 INTRODUCTION

Have you ever experienced a lift stop where nobody came in nor exit the lift car? Your lift ride to the destination floor is unnecessarily delayed. Frustrating, isn't it? Unnecessary lift stops are not just annoying for the passengers directly witnessing them but in general they negatively affect the service quality of all passengers. Unnecessary stops occur for several reasons, which are described with subtlety in Section 2. This paper considers only situations where the group controller brings a full lift to a landing and no passengers exit the car and none of the waiting passengers cannot board it because there is no room for them.

According to ISO standard 8100-32:2018 [1], "Means shall be provided to prevent an overloaded LCU from attempting to move away from a landing". Here LCU is an acronym for load-carrying unit. In practice this means that each lift is equipped with a load weighing device. Lift manufactures have used load weighing devices for a long time, in addition to their original safety purpose, among others to cut down unnecessary stops, which is referred to as *load bypass feature* [2]. In this feature, a lift starts bypassing registered landing calls when the car is loaded over a configurable limit, called *bypass load*. When there are only passengers travelling without any belongings, the load bypass feature works well in eliminating the unnecessary stops.

The situation changes quite much when passengers transport light objects with them like luggage, trolleys, stretchers, shopping carts, beds etc. Without loss of generality, this paper considers only luggage. It may happen that the floor area of a lift is fully occupied but the load is still below the bypass load limit, and as a result, unnecessary stops may occur. This issue has been recognized a long time ago. Strakosch [3] puts it in his book this way: "Elevator manufactures should be challenged to develop a means to reliably recognize when an elevator is filled by area rather than by weight, as is the current practice". Despite this open challenge and the fact that the issue has been known for a long time, it remained untouched for many years. Thanks to recent advances in computer vision hardware and software, the issue has gradually started to receive attention, both in industry (e.g., [4,5]) and academia (e.g., [6-13]).

This paper assumes that the floor occupancy information of lifts is available in the lift group controller and is used, in addition to load information, in the bypass feature which is in this case referred to as *load-area bypass feature*. No information about waiting passengers at lift lobbies is assumed to be known, except landing calls given by them. The feature is detailed in Section 3.

As far as we know, all previous papers either describe the issue on a general level without going into details, focus on development of a computer vision method for it, propose a new lift group control system using floor occupancy information of lifts, and/or report some experimental results. None of them though carries out a comprehensive analysis of how often unnecessary stops occur, whether they dependent on different factors, and how much key performance indicators are improved in conventional control buildings when using the load-area bypass feature in comparison with the load bypass feature, which is the main contribution of this paper.

This paper is organized as follows. Section 2 discusses in detail the reasons behind unnecessary stops and gives a definition for an unnecessary stop. Section 3 describes the load-area bypass feature together with key performance indicators used to assess its impact. Section 4 presents considered scenarios. Section 5 analyses the simulation results, and a conclusion follows in Section 6.

2 UNNECESSARY STOPS

Unnecessary stops occur for diverse reasons, and they can originate from all common call types: car calls, landing calls, and destination calls.

Consider first car calls. An unnecessary stop occurs if a passenger presses the wrong car call button, intentionally or accidentally, and none of the co-riders is going to that floor and no new passenger will board the car at the landing where the car call was given to. Suppose now that the given car call is correct. In this case an unnecessary stop may still occur if the passenger, who gave the call, for some reason exits the car at a wrong floor, for example too early before the lift reaches the destination floor of that call.

Consider next landing calls. An unnecessary stop occurs if a passenger gives a landing call in the wrong direction and none of the waiting passengers, including forthcoming passengers, is going in that direction from that landing and there is no car call given to that floor in the lift that will arrive to serve that call. For example, that may happen if the passenger presses both landing call buttons in the hope of getting a lift to arrive sooner, as the well-known misconception goes.

Suppose again that the call is correct. If now for some reason the passenger leaves the lobby before the serving lift arrives, for example, due to frustration with waiting, then an unnecessary stop may occur. Or the passenger just misses the serving lift due to poor signalization, for example, hall lanterns are dim, an audible lift arrival gong sound is quiet, or the lift lobby is overcrowded and getting in the serving lift in time is not possible. An unnecessary stop occurs, too, if the lift group control system dispatches a full car to the call and as a result, there is no room for the passenger.

Likewise, destination calls may result in unnecessary stops. In the worst case, there will be two unnecessary stops, one at the origin floor of the call and another at the destination floor.

A lift can travel from one floor to another without serving any passengers due to parking commands and such stops should not be considered as unnecessary. Therefore, in this paper, a lift stop is classified as *unnecessary* if during the stop no passengers leave or enter it and the load of the lift is greater than zero. In literature a few different names have been used for unnecessary stops: *useless stop* [2, 3], *redundant stop* [7,8], *wasted stop* [12, 13], and *false stop* [14].

As mentioned in Section 1, this paper considers only such unnecessary stops that originate from situations where the lift group controller brings a full lift to a landing and no passengers exit the car and the waiting passengers cannot board it because there is no room for them. Hence, unnecessary stops caused by other reasons including misbehaviour of passengers, congestion, parking commands, and poor signalization are left out of the scope.

3 LOAD-AREA BYPASS FEATURE AND KEY PERFORMANCE INDICATORS

This section begins with reconsidering the load bypass feature since it is used as a reference point. In this feature, a lift starts bypassing registered landing calls in its current direction of travel when the car is loaded over the bypass load limit, and bypassing happens until the car has enough room for more passengers, that is, the load is again below the limit. Usually, the bypass load limit is set to 60 – 80 % of the rated load of a lift, for example, to take into consideration cultural and building type differences in loading.

The load-area bypass feature uses floor occupancy information of lifts in addition to load information. Technically speaking, in the load-area bypass feature a lift starts bypassing registered landing calls if either A) measured load (in person) is greater than or equal to bypass load limit; or B) measured floor occupancy ratio (space demand of passengers and their luggage / rated load) is greater than predefined area threshold. Bypassing occurs until both measures - load and floor occupancy ratio - are below their limits.

The impact of the load-area bypass feature is measured by several key performance indicators (KPIs) including average waiting time (AWT) and average time to destination (ATTD) of passengers, carload factor (CLF), car area factor (CAF), as well as the number of unnecessary lift stops (ULS) and the number of unnecessary intermediate stops (UIS) of passengers. This paper reports passenger-based statistics rather than call-based statistics, e.g., waiting time of a passenger continues if the passenger is not able to enter the responding lift.

Carload factor is the largest load (in person) during the round trip of the lift in percentage of the rated load (in person). CLF is averaged over round trips. It is assumed in this paper that the weight of each piece of luggage is zero. Thus, load includes only passengers. *Car area factor* is the largest area (in person) occupied by passengers and luggage during the round trip of the lift in percentage of the rated load (in person). CAF is averaged over round trips, too. *Intermediate stop* (IS) of a passenger is a lift stop that occurs during a journey of the passenger except for stops at the origin and destination floors.

4 CONSIDERED SCENARIOS

To examine how much KPIs are improved when using the load-area bypass feature compared with use of the load bypass feature, and how they are dependent on different factors, a large set of hypothetical instances are formed, simulated and the resulting logs are analysed. The set is formed by varying lift group size, proportion of passengers with luggage, their luggage size, traffic pattern and intensity, as well as value of the floor occupancy threshold and measurement error. The following subsections give detailed information about the defined scenarios.

4.1 Lift group size

Four different low-rise hotel buildings are considered. Each building has one lift group, named as L2, L4, L6, and L8, respectively. The corresponding buildings are referred to by these group names, too. In each building the ground floor, which is indexed as 0, is the entrance floor, and populated floors start from floor 1. Lift groups are sized by following a common practice and two traffic patterns are considered. A traffic pattern can be characterized by ratios of traffic components: incoming, outgoing, and interfloor passengers [15].

Incoming passengers leave from the entrance floor and are destined to the populated floors of the building. *Outgoing* passengers leave the populated floors and travel to the entrance floor. *Interfloor* passengers travel only between the populated floors. Table 1 presents the proportions of the traffic components for traffic patterns used in the sizing of the lift groups. In these sizing simulations, all passengers travel without any belongings.

Table 1 Traffic patterns used in sizing simulations

Traffic pattern	**Traffic components [%]**		
	Incoming	**Outgoing**	**Interfloor**
Up peak	100	0	0
Two-way	50	50	0

More specifically, lift parameters and building populations are selected so that at traffic intensity of 12% of population / 5 minutes, AWT is less than 30 seconds and CLF is less than 80% in both traffic conditions. Lift and building parameters are shown in Table 2.

Table 2 Building information and lift parameters

Parameter / Group	**L2**	**L4**	**L6**	**L8**
Number of populated floors	6	13	21	24
Population per floor	57	59	54	57
Floor height [m]	3.6	3.6	3.6	3.6
Number of lifts	2	4	6	8
Rated load [persons]	13	17	24	26
Rated speed [m/s]	1.6	2.0	3.0	3.0
Acceleration [m/s2]	0.8	0.8	0.8	0.8
Jerk [m/s3]	1.2	1.2	1.2	1.2
Door width [mm]	1100	1100	1200	1300
Door closing time [s]	3.1	3.1	3.4	5.0
Door opening time [s]	1.4	1.4	1.4	2.3
Passenger transfer times [s] (in + out)	2.1	2.1	2.0	1.9
Photocell delay [s]	0.9	0.9	0.9	0.9
Start delay [s]	0.7	0.7	0.7	0.7
Advance door opening speed [m/s]	0.3	0.3	0.3	0.3
Advance door opening distance [m]	0.15	0.15	0.15	0.15

In addition, groups are equally balanced, i.e., their AWTs are about the same. Table 3 gives the AWT and CLF of the sizing simulations for all groups and both in up peak and two-way traffic patterns as well as in the last row the number of calls in percentage that have waiting time < 60 s for all groups in up peak traffic. For excellent service level it is recommended that in up peak traffic 98% of all waiting times should be below 60s [16] and AWT should be below 15s [17]. From Table 3 one sees that L2 provides excellent and other groups good service level, but very close to excellent.

Table 3 AWT, CLF and cumulative percentage of waiting times at 60 s in sizing simulations at 12 % traffic intensity for all groups and both traffic patterns (except the cumulative %)

KPI	Traffic pattern / Group	L2	L4	L6	L8
AWT [s]	Up peak	14.7	15.2	15.5	15.1
	Two-way	17.7	19.1	19.2	18.6
CLF [%]	Up peak	35.2	52.6	54.2	61.5
	Two-way	25.6	34.8	36.5	39.5
# Waiting times < 60 s [%]	Up peak	99.5	97.4	95.8	95.7

4.2 Passenger group ratios and luggage size

Two separate passenger groups are considered: passengers without luggage and passengers each with one piece of luggage, referred to as *without luggage* and *with luggage* groups, respectively. Ratios of 10%, 20%, 30%, and 50% are considered for with luggage group. For example, 10% means that 10% of the population travel with one piece of luggage each and 90% of the population travel without any luggage.

Three luggage sizes are defined, 1, 2, and 3 units. 1 unit corresponds to the size of a single person. For example, size 2 means that the space demand of a passenger with luggage is 3 passengers. As mentioned in Section 3, the weight of each piece of luggage is zero.

4.3 Traffic patterns and intensity

Several different traffic patterns are studied. Table 4 presents the proportions of the traffic components for each considered traffic pattern and for both passenger groups.

Table 4 Traffic patterns used in analyses

Traffic pattern	Passenger group	Traffic components [%]		
		Incoming	Outgoing	Interfloor
Down peak	With luggage	0	100	0
	Without luggage	0	100	0
Two-way	With luggage	50	50	0
	Without luggage	50	50	0
Mixed	With luggage	25	25	50
	Without luggage	25	25	50
Hotel	With luggage	0	100	0
	Without luggage	45	55	0

Traffic intensity is varied, starting from an arrival rate of 4% of population / 5 minutes, stepwise increasing the rate 1% amount at a time, and ending at the arrival rate of 15%. At each intensity, traffic is simulated for 120 minutes to reduce the variance of the results.

4.4 Bypassing trigger values

In load-based bypassing, it is assumed that there is no error in the load measurement, and load is measured in the number of passengers. 80% of the rated load, rounded to nearest integer, is used as a trigger value, and its value for each group is given in Table 5 in the last row.

Table 5 Trigger values for both area-based and load-based bypassing

Bypass feature, Trigger policy / Group	**L2**	**L4**	**L6**	**L8**
Area-based, No space for 1 passenger	0.924	0.942	0.959	0.962
Area-based, No space for 2 passengers	0.847	0.883	0.917	0.924
Area-based, No space for 3 passengers	0.770	0.824	0.875	0.885
Area-based, No space for 4 passengers	0.693	0.765	0.834	0.847
Load-based, ~ 80 % load [persons]	10	14	19	21

In area-based bypassing, four different trigger values are investigated, no space for 1, 2, 3, or 4 passengers. Their values for each group are listed in Table 5 in the first four data rows. Some uniformly distributed error is considered in the measurement of floor occupancy of a lift: 0 %, 5 %, and 10 %. For example, if the total space demand of passengers and luggage is 15 in a 20-person car after a stop, and the measurement error is 5 %, then the measured floor occupancy is uniformly sampled from range [0.7125 (=15/20*0.95), 0.7875 (=15/20*1.05)].

5 SIMULATION RESULTS

The formed set of scenarios contains 34 560 different instances in total. All of them are simulated in Building Traffic Simulator, [18, 19], which is KONE's internal tool used for traffic analyses as well as in research and development activities.

Group controller is *conventional control* with up and down call buttons at every landing, except the highest and lowest levels where on both is only one landing call button. Readers interested in the technical details of the controller are referred to reference [20].

Section 5.1 analyses instances in which only the load bypass feature is on, to see how much there are unnecessary stops in general, are they dependent on different factors such as traffic pattern and intensity, and how much AWT and ATTD of passengers vary between with luggage and without luggage passenger groups. Section 5.2 in turn investigates the impact of the load-area bypass feature on the KPIs.

5.1 Simulation results for scenarios with the load bypass feature

In instances with the load bypass feature, there are 13,159,539 lifts stops and out of them 698,577 are unnecessary, Table 6. This means that 5.31% of lifts stops are unnecessary.

Table 6 Number of lift stops and # ULS both in absolute and relative values in the load bypass scenarios

# Lift stops	**# ULS**	**# ULS [%]**
13,159,539	698,577	5.31

Fig. 1 gives the histogram of the relative number of ULS per considered scenario with the load bypass feature and cumulative % (on the secondary axis). From this figure one observes that ULS occur quite rarely, in 88.06% of instances their relative number is less than 5%, but there are some scenarios where ULS occur often; in 117 scenarios more than 50% of lift stops are unnecessary.

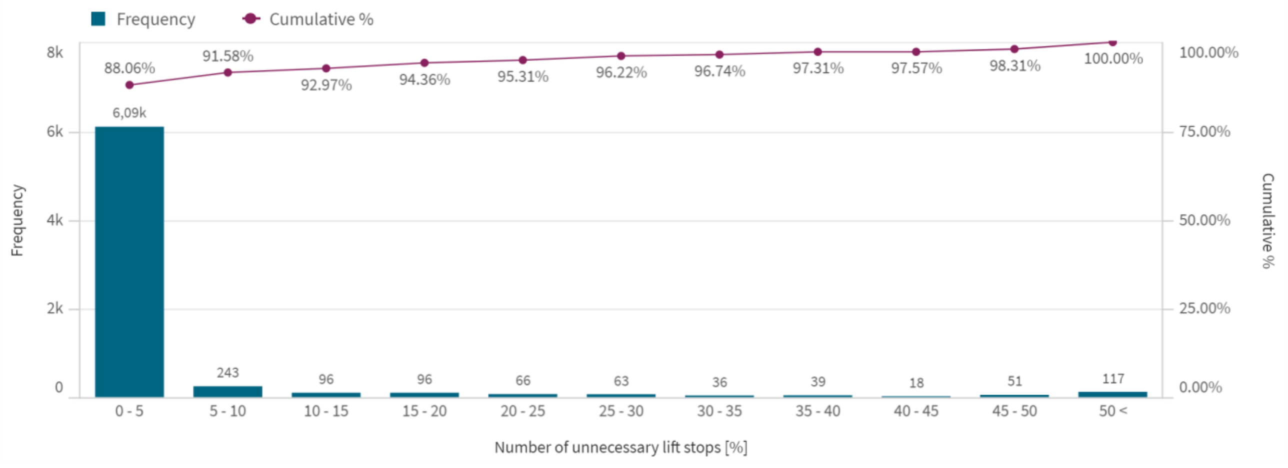


Figure 1 Histogram of the relative number of ULS per scenario and cumulative %

In instances with the load bypass feature, 13,854,492 passengers are served in total, they experience 38,627,808 ISs, and out of them 7,650,306 are unnecessary, i.e., 19.81% are unnecessary, Table 7.

Table 7 Number of passengers served, IS and UIS in the load bypass scenarios

# Passengers	# IS	# UIS	# UIS [%]
13,854,492	38,627,808	7,650,306	19.81

Fig. 2 displays the histogram of the number of UIS in instances with the load bypass feature and cumulative %. The majority of passengers, 87.55%, do not see any UIS during their journeys, but some passengers experience lots of them; 96 passengers face 21 unnecessary intermediate stops.

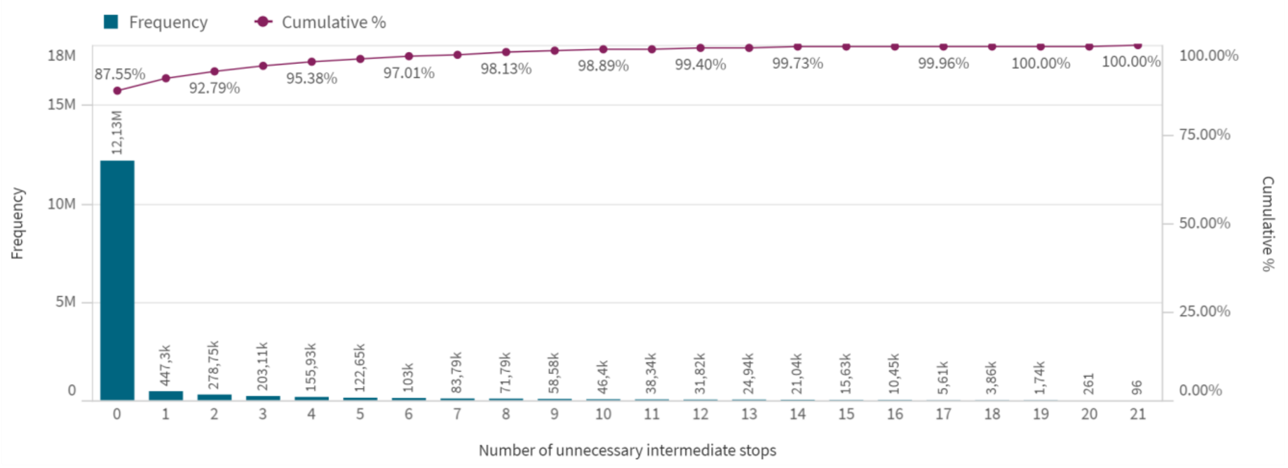


Figure 2 Histogram of the number of UIS and cumulative %

Consider next how the unnecessary lift stops are dependent on different factors. Fig. 3 shows the number of ULS both in absolute values (bars) and relative values (line, on the secondary axis), per traffic intensity over all instances with the load bypass feature. It is clear from this figure that the number of ULS increases as a function of traffic intensity and in an exponential fashion, though the growth rate seems to be decreasing.

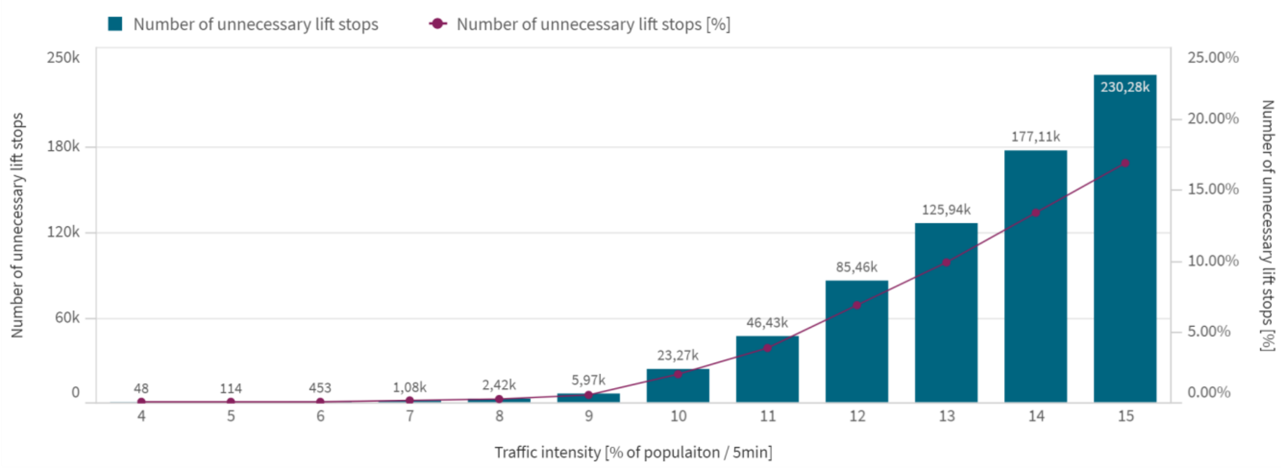


Figure 3 Number of ULS in the load bypass scenarios per traffic intensity

Table 8 reports the number of ULS per traffic pattern over all instances with the load bypass feature, both in absolute and relative values. According to it, down peak generates the largest number of ULS, followed by the hotel traffic. The reason is that in both traffic patterns the proportion of outgoing traffic component is large, and outgoing passengers are travelling to a single point, the entrance level located at the lowest level.

Table 8 Number of ULS per traffic pattern over all instances with the load bypass feature

Traffic pattern	Down peak	Hotel	Mixed	Two-way
# ULS	323,922	265,095	54,237	55,323
# ULS [%]	10.42	8.23	1.47	1.76

ULS are not only dependent on traffic intensity and pattern, but they are also dependent on how many passengers travel with luggage. In Fig. 4, the left-hand side bar chart illustrates the number of ULS per ratio of luggage passenger group over all instances with the load bypass feature whereas the right-hand side illustrates the number of ULS per luggage size over all instances with the load bypass feature. Based on this figure one can say that the more passengers with luggage there are and the bigger luggage size, the more unnecessary stops there are.

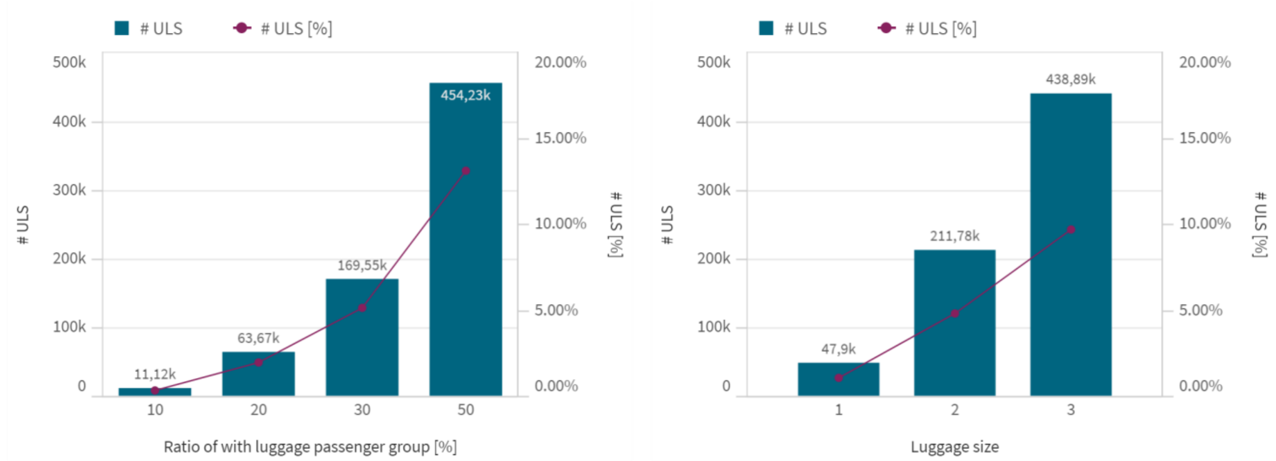


Figure 4 Number of unnecessary lift stops per ratio of luggage passenger group (left) and per luggage size (right) in instances with the load bypass feature

Fig. 5 depicts the number of ULS per floor and per traffic pattern for group L8. Only a single group is considered now since each building has a different number of floors. Results for other groups are similar. From this figure one sees that the largest number of ULS occur at the lowest populated levels. To be precise, for down peak, hotel, and two-way traffic patterns the largest number is at level 1 or 2, but for the mixed traffic it is at a bit higher, at level 5 or so.

One of the major reasons is that in call allocation, for each lift, the service order of car calls given inside of it and landing calls asssigned to it is determined according to a full collective control [20,21]. In general, the collective control works as follows: “The lift stops to answer both car calls and landing calls in the lift direction of travel, in floor sequence. When no more calls are registered in the lift direction ahead of the lift, the lift moves to the furthest landing call in the opposite direction, if any, reverses its direction of travel, and answers the calls in the new direction” [2]. Thus, for example in down peak, each lift starts serving landing calls downwards from the highest call allocated to it after dropping off passengers and reversing its direction of travel at the entrance level.

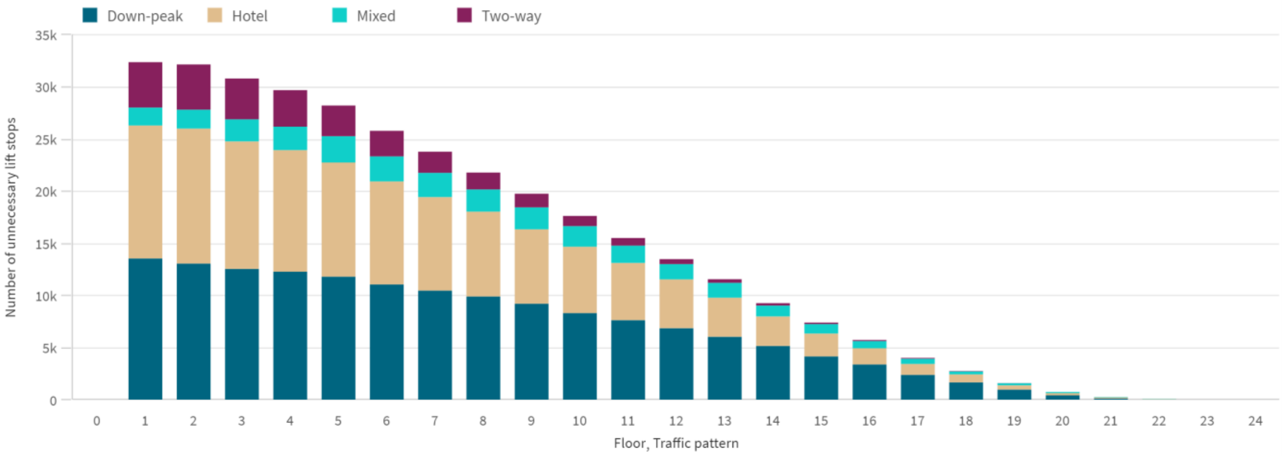


Figure 5 Number of unnecessary lift stops per floor and traffic pattern for L8 group

It follows from this ULS distribution that service quality is not fairly distributed between the levels, as can be verified from Fig. 6 that shows AWT per floor and direction over all the load bypass scenarios. For example, AWT at level 1 downwards is more than tenfold higher compared with the highest levels.

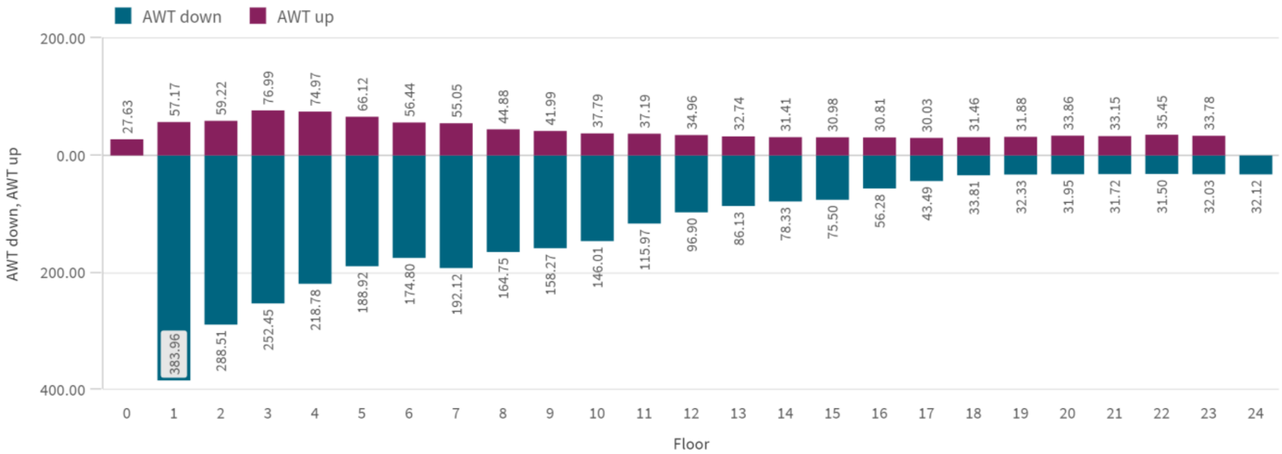


Figure 6 AWT per floor and direction over all instances with the load bypass feature

Neither is service quality fairly distributed between different passenger groups. AWT and ATTD per luggage size and space demand are provided in Fig. 7. Recall that luggage size x means that the space demand of with luggage passenger is x+1 units and the space demand of passenger without luggage is 1. It is clear from this figure that the larger the belongings of passengers are, the longer their waiting times and times to destinations are. For example, in scenarios where luggage size is 3, AWT (ATTD) of passengers travelling without any belongings is 134.26 (197.57) seconds but AWT (ATTD) is 416.17 (483.90) seconds for passengers travelling with luggage.

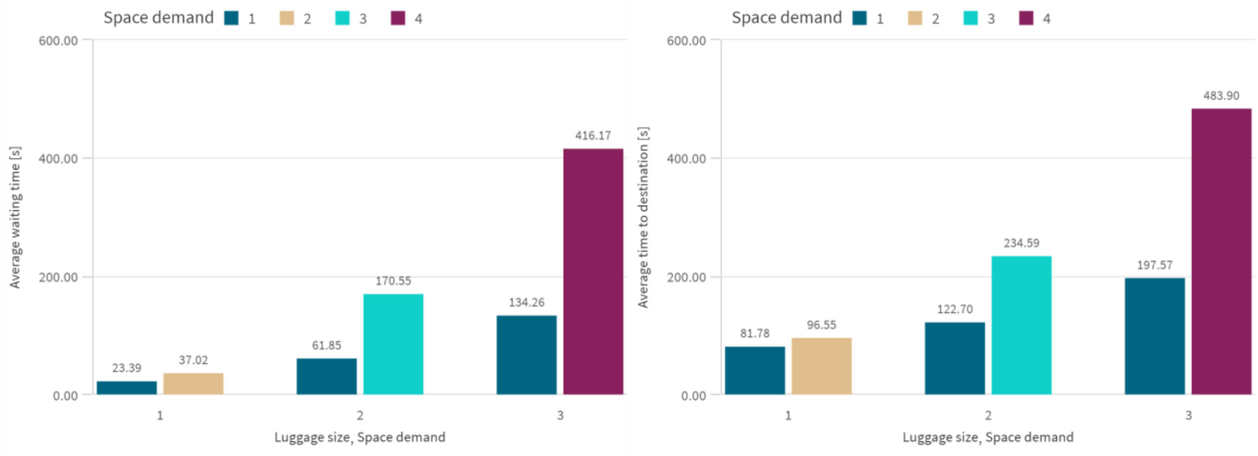


Figure 7 AWT (left) and ATTD (right) per luggage size and space demand over all instances of the load bypass feature

5.2 Impact of the load-area bypass feature

This section investigates the impact of the load-area bypass feature on the KPIs. Overall improvements are reported in Table 9. # ULS and # UIS for the load-area bypass feature are averages over different trigger values used in the feature.

Table 9 Overall improvements of the load-area bypass feature on the KPIs

Feature / KPI	AWT	ATTD	# ULS	# UIS	CLF [%]	CAF [%]
Load bypass	109.84 s	171.48 s	698,577	7,650,306	21.52	34.40
Load-area bypass	24.16 s	79.26 s	33,027.00	298,730.75	21.03	33.71
Improvement [%]	78.00	53.78	95.27	96.10	2.28	2.01

According to this table, the impact of the load-area bypass feature on AWT and ATTD is significant. Overall AWT is reduced by 78% and ATTD by about 54%. The reduction is dependent on traffic pattern and intensity as can be seen from Table 10 and Fig. 8, respectively.

Table 10 AWT and ATTD improvements of the load-area bypass feature per traffic pattern

Traffic pattern	Down peak	Hotel	Mixed	Two-way
AWT improvement [%]	86.88	87.08	32.30	61.54
ATTD improvement [%]	67.93	69.46	15.39	32.40

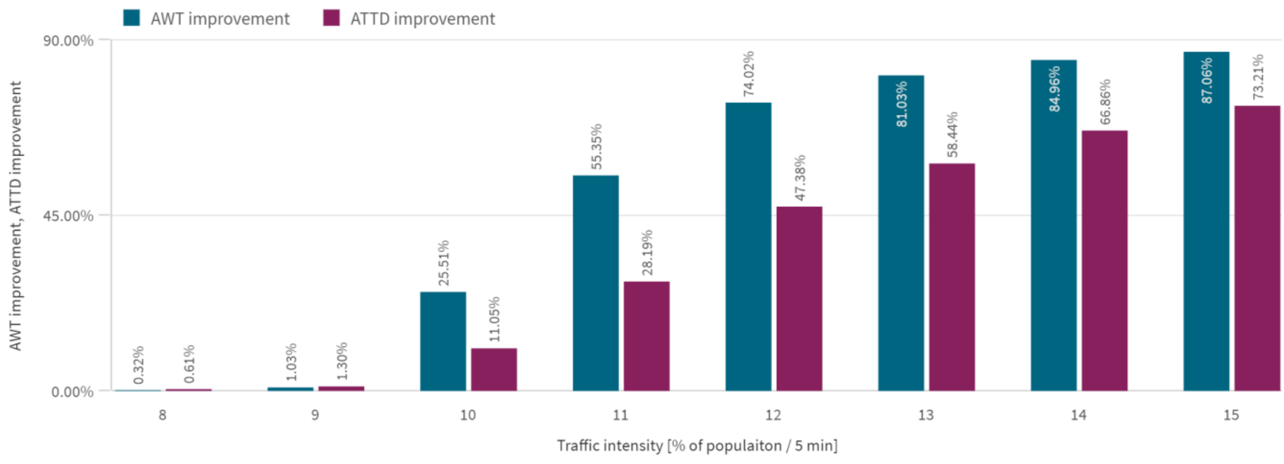


Figure 8 AWT and ATTD improvements of the load-area bypass feature per traffic intensity

According to Table 11, improvements in AWT and ATTD are also slightly dependent on the trigger value used in the load-area bypass feature.

Table 11 AWT and ATTD improvements of the load-area bypass feature per trigger value

Trigger value	**No space for 1**	**No space for 2**	**No space for 3**	**No space for 4**
AWT improvement [%]	75.96	78.23	78.84	78.97
ATTD improvement [%]	51.91	53.83	54.53	54.86

The load-area bypass feature does not only shorten waiting times and times to destinations, but it also makes the service fairer between floors and between different passenger groups, as can be verified from Fig. 9 and 10, respectively, in comparison with Fig. 6 and 7.

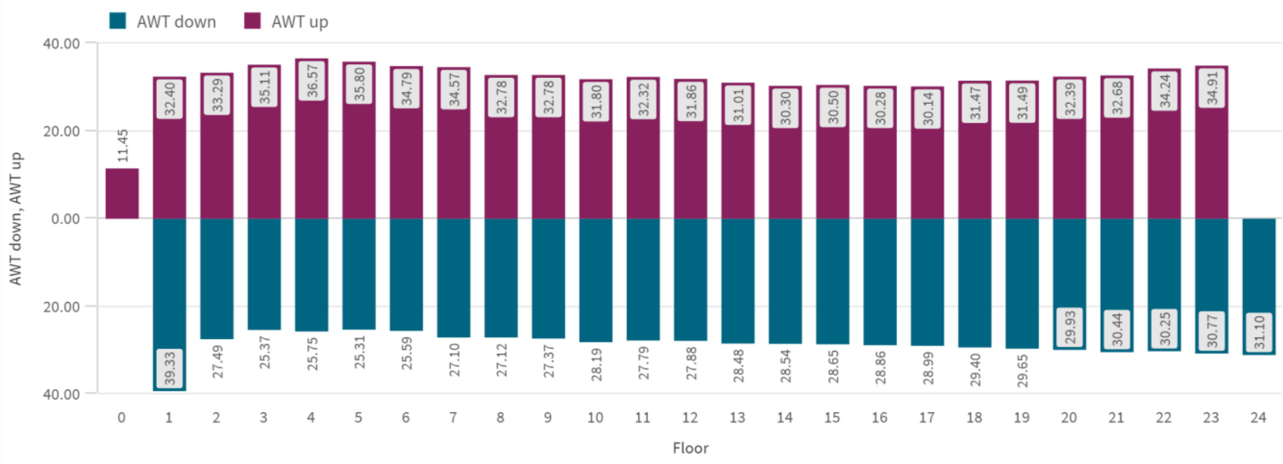
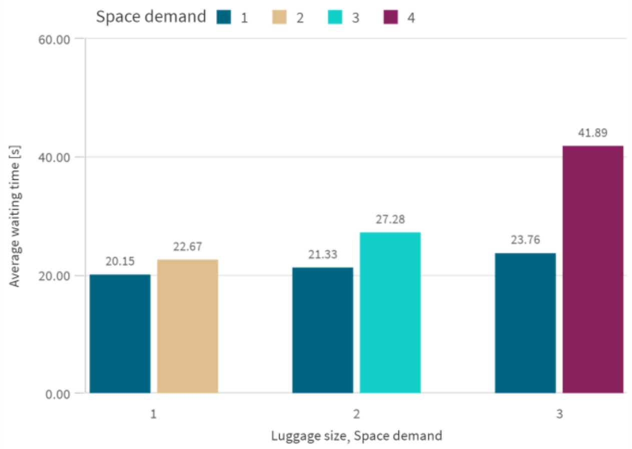


Figure 9 AWT per floor and direction over all instances of the load-area bypass feature

The impact of the load-area bypass feature on the number of ULS (UIS) is very big; more than 95% (96%) of unnecessary stops are eliminated in general. The reduction is dependent on traffic patterns as can be seen from Table 12. As before, # ULS for the load-area bypass feature is average over different trigger values used in the feature.



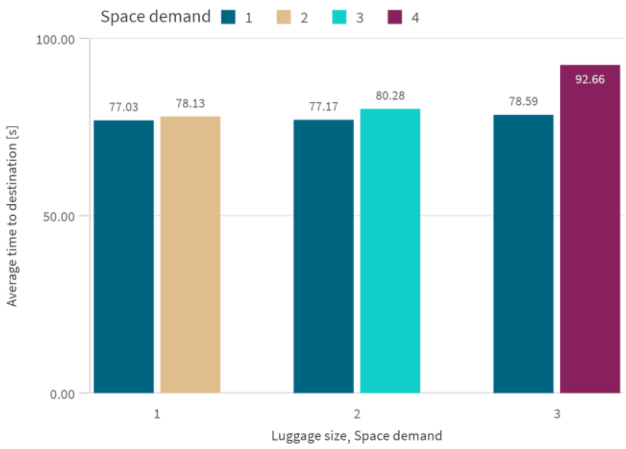


Figure 10 AWT (left) and ATTD (right) per luggage size and space demand over all instances of the load-area bypass feature

Table 12 Reduction in # ULS per traffic pattern in instances with load-area bypass feature

Traffic pattern	Down peak	Hotel	Mixed	Two-way
# ULS	10,320.00	12,555.25	7,282.00	2,869.75
Improvement [%]	96.81	95.26	86.57	94.81

The following example gives an explanation for why the reduction in the number of ULS is worse in mixed traffic.

Consider a simple situation. Travel direction of lift A is upwards, it is full, it is about to stop at level X, which is above the entrance floor, to serve a car call, and it has car calls above level X. If now someone gives a landing call from level X upwards, the landing call cannot be allocated to lift A since it is full, thus it is allocated to some other lift, say B. Suppose that during the stop at level X, some passengers leave lift A, but the load of it is still above the bypass load limit. Allocation of the landing call cannot be changed from B to A since bypass load is considered in the call allocation; calls are allocated up to bypass load of the lift. Nevertheless, the waiting passengers enter the first lift in their direction of travel, and they load the car up to rated capacity. Therefore, if all passengers behind the landing call entered lift A and lift B has no car calls to level X, then unnecessary stop occurs; when lift B arrives at level X, there is nobody entering or exiting the car. Such situations occur only when there is interfloor traffic.

The reduction in the number of ULS is also dependent on the trigger value of area-based bypassing as can be seen from Table 13.

Table 13 Reduction in the number of ULS per trigger value of the load-area bypass feature

Trigger value	No space for 1	No space for 2	No space for 3	No space for 4
# ULS	80,861	31,686	12,579	6,982
Improvement [%]	88.42	95.46	98.20	99.00

From a ULS reduction point of view, the smaller the trigger value, the better. Nevertheless, setting the trigger value too low likely negatively affects handling capacity. Therefore, one good option is to set the trigger value based on luggage size.

The reduction in the number of ULS is dependent on the measurement error, too, Table 14. As before, here # ULS is average over different trigger values used in the feature.

Table 14 Reduction in # ULS per measurement error value of the load-area bypass feature

Measurement error [%]	**0**	**10**
# ULS	9,550.75	14,525.00
Improvement [%]	95.90	93.76

According to Table 9, in general it seems that the load-area bypass feature has a small impact on CLF and CAF. A possible reason is that when a lift stops to pick up more passengers, all of them are loaded or up to rated load of the lift, independent of trigger values used in the feature.

6 CONCLUSION

A stop is unnecessary if a lift stops to serve a call, but no passengers enter or exit the lift. Such stops are not just annoying for the passengers directly witnessing them but in general they negatively affect the service quality of all passengers. There are many reasons for occurrence of them. In this paper the focus was on situations in which lift stops to pick up passengers, but nobody enters the car since the waiting passengers consider the car full and nobody exits the car.

This paper studied whether the number of unnecessary stops is dependent on different factors and how much passenger service quality is improved in conventional control buildings when the floor occupancy information of lifts is used, in addition to load, in the bypass feature by analysing simulation results from a large set of hypothetical instances.

Simulation results with the load bypass feature showed that the number of unnecessary lift stops is dependent on traffic intensity and pattern, the number of passengers with luggage, and luggage size. Results also pointed out that service quality can be unfairly distributed between floors and passenger groups due to the unnecessary stops.

Simulation results with the load-area bypass feature demonstrated that the majority of the considered unnecessary stops can be eliminated and service quality can be significantly improved. The reduction is dependent on multiple factors such as traffic intensity, traffic pattern, trigger value, and the measurement error. The load-area bypass feature does not only improve service quality, but it also makes the service fairer between floors and between passengers with and without belongings.

It is, though, difficult to estimate the impact of load-area bypass feature in a certain real building as it is dependent on so many different factors, as was seen. Also, things left out the scope probably influence the results a lot. Thus, to get a better understanding about the real impact, experiments in real buildings need to be conducted.

Other future research includes use of information in a lift group controller about how many passengers are waiting at lift lobbies as well as what are their space demands in reducing unnecessary stops further, and an impact investigation of load-area bypass feature on different building types such as shopping malls and during construction of buildings.

REFERENCES

[1] ISO 8100-20:2018, *Lifts for the transport of persons and goods - Part 20: Global essential safety requirements (GESRs)* (2018).

[2] Barney G., Al-Sharif L., *Elevator Traffic Handbook: Theory and Practice*. 2nd ed., Routledge, Taylor & Francis Group (2016).

[3] Strakosch G. R., *The Vertical Transportation Handbook*. 3rd ed., John Wiley & Sons (1998).

[4] O'Laughlin J., "Improving Elevator Performance by Monitoring Elevator Cab Volume". *Elevator World*, Nov 1 (2008).

[5] CabVision, Adams Elevators, [https://www.adamscanada.ca/Specific_pdfs_HW/cabvisionSellSheet_web.pdf], available on June 7, 2022.

[6] Vareljian V., Zou J., "Intelligent Elevator Control by Application of Computer Vision". In Proceedings of the 2006 conference on *Advances in Intelligent IT*: *Active Media Technology 2006*, pp. 182-187 (2006)

[7] Sahin Y.G., Uzunbayir S., Akçay M.B., Yildiz E., "Real-Time Monitoring of Elevators to Reduce Redundant Stops and Energy Wastage". In Proceedings of the 2013 *International Conference on Systems, Control and Informatics*, 264-269 (2013).

[8] Mohamudally F., Inn C. S., Yeong L. S., and Chong C. W., "Estimating free space in an elevator's confined environment". TENCON 2015 - 2015 IEEE Region 10 Conference, 1-6 (2015)

[9] Zou J. and Zhao Q., "Occupancy detection in elevator car by fusing analysis of dual videos". In Proceedings of the *2017 13th IEEE Conference on Automation Science and Engineering (CASE)*, 906-911 (2017)

[10] Feigang T., Kaiyuan L., Lifeng L., Yang W., "An Intelligent Detection System for Full Crew of Elevator Car". In proceedings of the *2018 11th International Conference on Intelligent Computation Technology and Automation (ICICTA)*, 183-185 (2018)

[11] Yamauchi T., Ide R., Sugawara T., "Fair and Effective Elevator Car Dispatching Method in Elevator Group Control System using Cameras". *Procedia Computer Science*, Vol. 159, 455-464 (2019)

[12] Wang S. et al, "Smart Elevator Dispatching and Optimization through Deep Learning of Usage Patterns". In Proceedings of the *2019 IISE Annual Conference*, 1498-1503 (2019).

[13] Wang S. et al, "Smart dispatching and optimal elevator group control through real-time occupancy-aware deep learning of usage patterns". *Advanced Engineering Informatics*, Vol 48, pp 101286 (2021)

[14] Gerstenmeyer S., Peters R., Smith R., "Departure Delays in Lift Systems". *Transportation Systems in Buildings*, Vol. 2, No. 1 (2018).

[15] Siikonen M.-L., "Elevator traffic simulation". *Simulation*, Vol. 61, No. 2, 257-267 (1993).

[16] Fortune J. W., "Elevatoring high rise buildings". International Conference on Tall Buildings, Singapore (1984).

[17] Siikonen M.-L., “Planning and Control Models for Elevators in High-Rise Buildings”. PhD Thesis, Helsinki University of Technology (1997)

[18] Leinonen, R., “Building Traffic Simulator.” Master of Science thesis, Helsinki University of Technology (1999).

[19] Siikonen M.-L., Susi T., and Hakonen H., “Passenger traffic flow simulation in tall buildings”. *Elevator World*, Vol. 49, No. 8, 117-123 (2001).

[20] Tyni T., Ylinen J., “Genetic algorithms in elevator car routing problem”. In *Proceedings of the Genetic and Evolutionary Computation Conference, GECCO 2001* (2001).

[21] Ruokokoski M., Sorsa J., Siikonen M.-L., and Ehtamo H., “Assignment formulation for the Elevator Dispatching Problem with destination control and its performance analysis”, *European Journal of Operational Research*, Volume 252, Issue 2, 397-406 (2016).

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BIOGRAPHICAL DETAILS

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Generation and Application of Dynamic Lift Kinematics

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Keywords: kinematics, lift, elevator, dynamic profile, ideal lift kinematics, twin lift system, 2 cars per shaft, multi, multi-dimensional lift system, simulation

Abstract. Performance time is a measure of the time it takes a lift to travel between floors and is crucial to delivering the highest possible handling capacity and lowest passenger waiting times. To calculate performance time and to enable a lift to deliver a comfortable trip leads to a need to understand lift kinematics. Lift kinematics is the study of the motion of a lift car in a shaft without reference to mass or force. When generating lift kinematics, it is normal to consider the travel distance, velocity, acceleration, and jerk; these inputs can be used with well-known equations to determine the time in flight, and a reference speed profile for the lift drive. However, in advanced lift applications, there are additional requirements for the deceleration not to be the same as the acceleration. The jerks may also be different and sometimes it is desirable to change speed part way through a trip. This paper addresses the generation of dynamic lift kinematics to meet these requirements and discusses their application.

1 INTRODUCTION

One method of monitoring a lift is to use an accelerometer to produce a kinematic profile which will provide information on how smooth the journey is. In order to analyse the results of these monitors, reference velocity profiles are needed. Variable speed drives can be programmed to match reference velocity profiles so generating kinematic profiles is useful for driving lifts too. The more control one has over their kinematic profiles, the more accurate the measurements can be, and the more power the dispatcher has over the position of the lift car over time. This paper will demonstrate how an updated model can produce kinematic profiles with fewer limitations than previous models have offered.

In previous papers regarding lift kinematics, equations have been produced which model symmetric profiles [1] and asymmetric profiles [2]. The authors have already detailed the equations in Dynamic extension for Ideal Kinematics [3], this paper will present the same logic but at a higher level and will focus more on the implementation than on the maths.

1.1 Definitions

symmetric profile
the profile of a journey with one target velocity, the same acceleration as deceleration and four identical jerk values. See Fig. 1

asymmetric profile
the profile of a journey with one target velocity but different target acceleration and deceleration or differing jerk values. See Fig. 2

dynamic profile
the profile of a journey with multiple target velocity values. Acceleration and jerk can also vary. See Fig. 3

period
a section of time where the lift is at constant jerk. See Fig. 4

phase
a section of time where the lift is changing from one speed to another including the time it remains at

its final speed. A phase starts and finishes with acceleration of 0 and contains a maximum of four periods. See Fig. 4

journey
a section of time where the lift is changing displacement from when the lift begins to move, to when it reaches its destination. Contains a minimum of two phases. See Fig. 4

1.2 Three types of profile

There are three types of kinematic profile that will be referred to in this paper:

1.2.1 Symmetric Profile

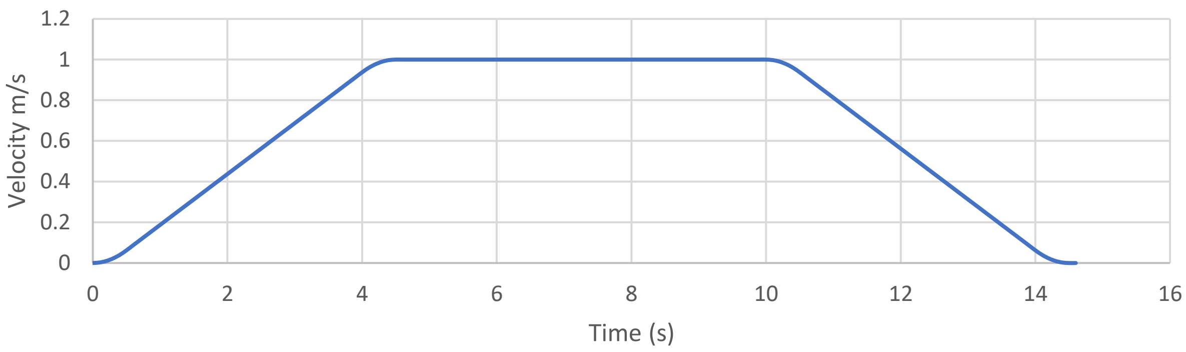

Fig. 1 Symmetric Profile

Fig. 1 shows a profile produced when a symmetric model has been used to plot the kinematic profile of a lift. This assumes that the lift accelerates and decelerates at the same rate which is what most lift systems aim to do in order to provide the smoothest ride quality for the passengers.

The equations for plotting a symmetric profile can be found in 'Ideal Lift Kinematics' by Peters [1].

1.2.2 Asymmetric Profile

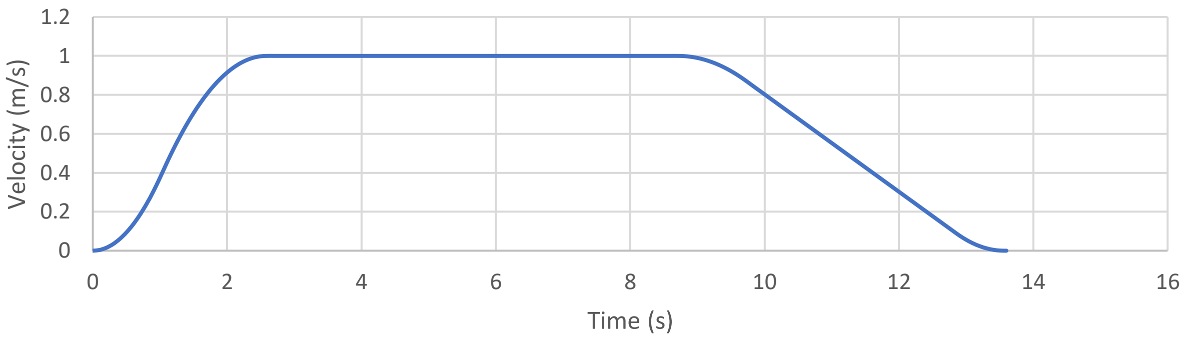

Fig. 2 Asymmetric Profile

Fig. 2 shows a profile when an asymmetric model has been used to plot the kinematic profile of a lift. Like the symmetric profile, this model assumes that there will only be one target velocity, however, it allows for different acceleration and deceleration values as well as differing jerk values.

Some cheaper or older lifts have asymmetric profiles due to the limitations of the drive. By being able to model profiles like this, these asymmetric lift systems can be accurately measured instead of the monitoring system attempting to best fit the data to a symmetric model. The other use of asymmetric modelling is in improving the performance of systems with two cars per shaft. For example, a lower deceleration may be used when the two cars need to be moved closer than allowed by the preferred safety distance. The safety distance between two cars is a function of the car's kinematics. By reducing the car's velocity, the cars can come closer together without compromising safety.

These profiles can be produced using the equations given in 'Quality and quantity of service in lift groups' by Gerstenmeyer [2]. The equations are an extension to the previous ideal lift kinematic equations meaning they can model symmetric and asymmetric equations.

1.2.3 Dynamic Profile

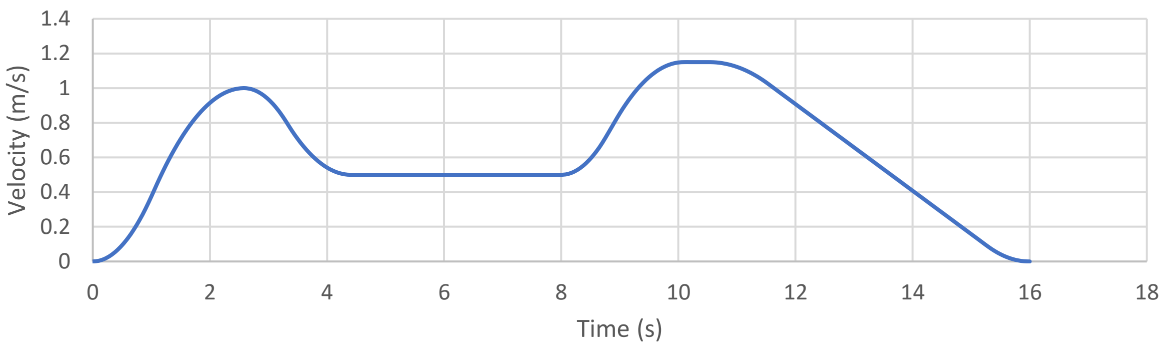

Fig. 3 Dynamic Profile

Fig. 3 shows a profile when a dynamic model has been used to plot the kinematic profile of the lift. This type of profile is occasionally seen in systems with a very long levelling delay where, towards the end of its journey, the lift decelerates to a reduced constant speed which it continues at until it levels with its destination floor. As is the case with lifts following an asymmetric profile, it is useful to monitor these types of systems instead of attempting to best fit them to a symmetric profile.

The dynamic model is also useful in systems with multiple cars. Reducing the velocity of a car at appropriate times can reduce the required safety distance between two cars. In instances where one car is blocking the path of another, travelling at a slower speed to allow more time for the blocking car to be moved away may be more acceptable to passengers than stopping the car completely. Gerstenmeyer states that the resulting increase in performance is particularly valuable to multi-dimensional lift systems with more than two lift cars per shaft. [2].

1.3 Three segments of a profile

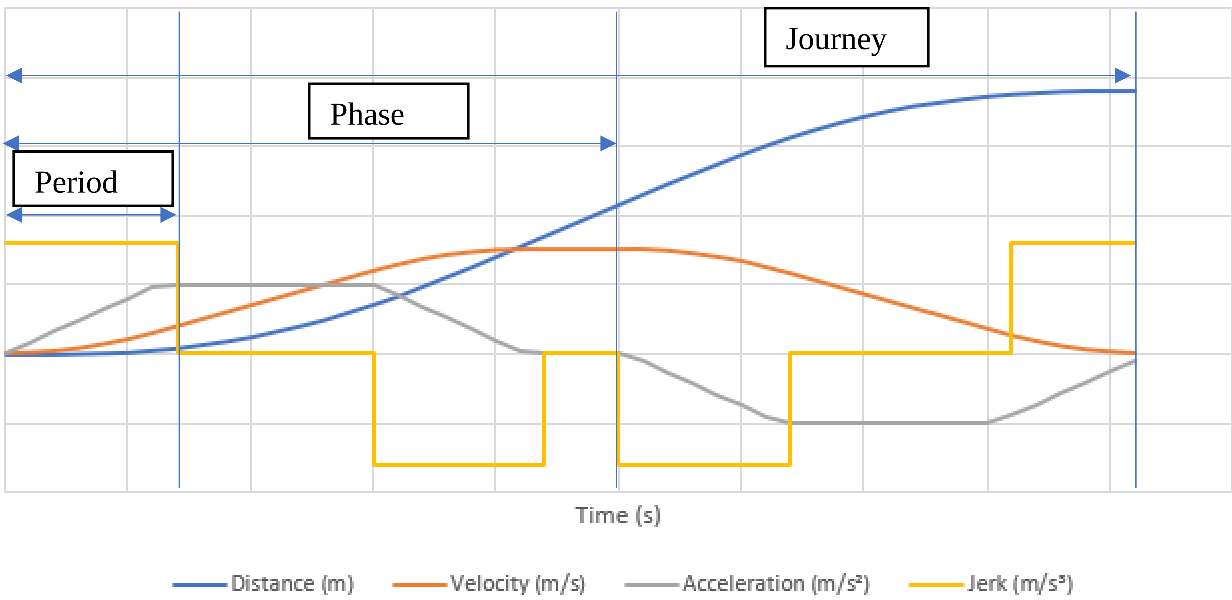

Fig. 4 Period, Phase and Profile labelled profile

Fig. 4 shows the kinematic profile of one symmetric journey. The first period and phase, and the journey are labelled.

2 OVERVIEW OF PREVIOUS RESEARCH

2.1 Previous Work

2.1.1 Analytical Method

Peters provided a set of equations which model the kinematic profile of a symmetric journey [1]. Each journey is divided into seven periods, each with their own set of equations. Each equation does the entire integration including the addition of the starting value at the previous period. This model provides a straightforward set of individual equations which do not approximate each integration like the computation method does. These equations are transparent and functional but very long and lack flexibility. This is also the method described in Annex 2 of Guide D [4].

Gerstenmeyer provided a set of equations which model the kinematic profile of an asymmetric journey [2]. This uses similar logic to the symmetric model however allows four different jerk inputs and two different acceleration values for the two phases involved. Whilst this improves the flexibility of the model, it also makes the equations even longer and harder to implement.

In the cases where a lift cannot reach the inputted velocity or acceleration, Peters proposed alternative models called ‘case B’ and ‘case C’ [1], Gerstenmeyer however proposed using the same equations by first reducing the velocity and acceleration to the maximum possible values that can be reached [2].

2.1.2 Computational Method

Computational integration methods include quadrature rule, generalised midpoint rule, adaptive algorithms and extrapolation. These methods use calculations which approximate integration to find the profile values without long equations. This method is far more flexible than the analytical method as it does not rely on period separations. However, the approximation required in the computational method decreases the accuracy of the profile. [5]

2.2 Authors’ contribution

The authors have derived an alternative set of equations which map onto the existing equations but allow for more flexible input parameters thus allowing the controller to have more flexibility over the shape of a lift’s kinematic profile. The new equations use a combination of analytical and computational techniques and use the Gerstenmeyer method for dealing with invalid input parameters [2].

3 METHOD

As the dynamic model is an extension of the asymmetric model, which is an extension of the symmetric model, the dynamic method should be applicable to all profile models.

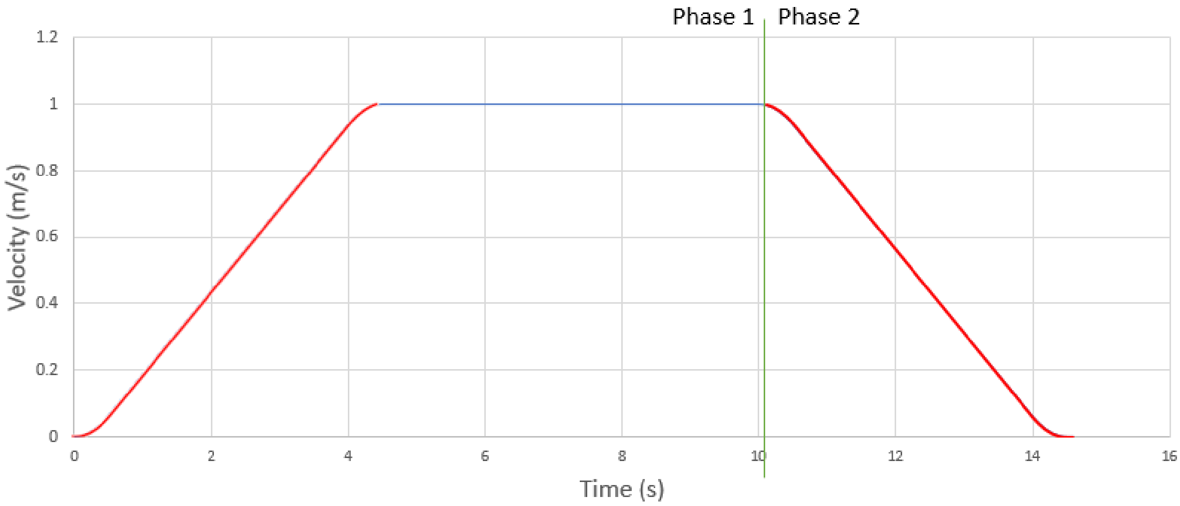

Figure 5 Symmetric phases

Each symmetric profile has two phases and the second phase mirrors part of the first phase. As seen in Figure 5, the two red sections have the same shape in reverse and thus phase 2 can be calculated using the same equation set as phase 1 after some of manipulation.

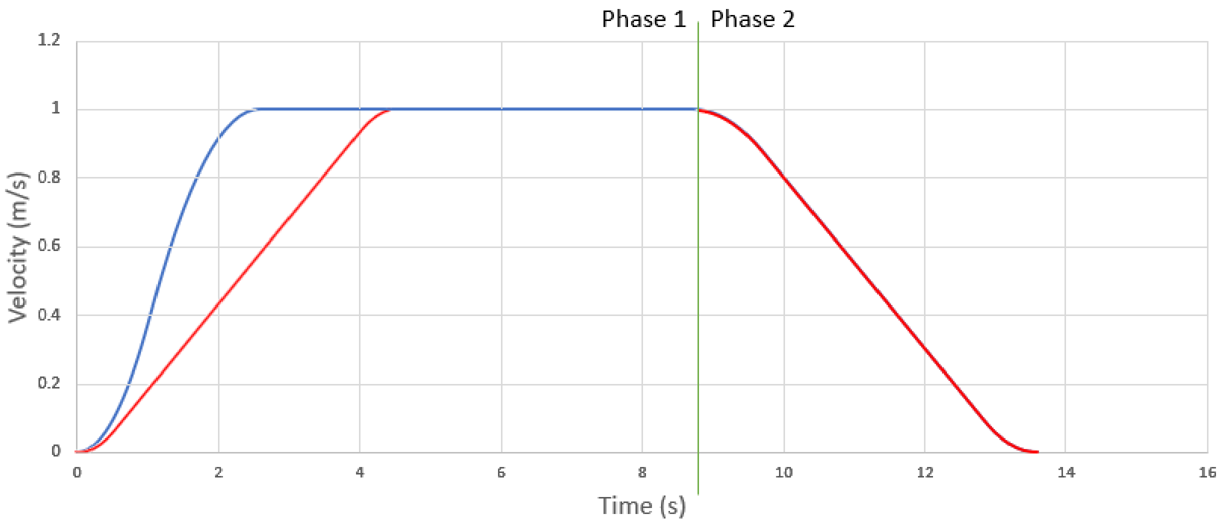

Figure 6 Asymmetric phases

If the acceleration and deceleration do not match, phase 2 is no longer a mirror image of phase 1 however it can still be calculated using the same equation set and then reversed as seen by the first red plot in Figure 6.

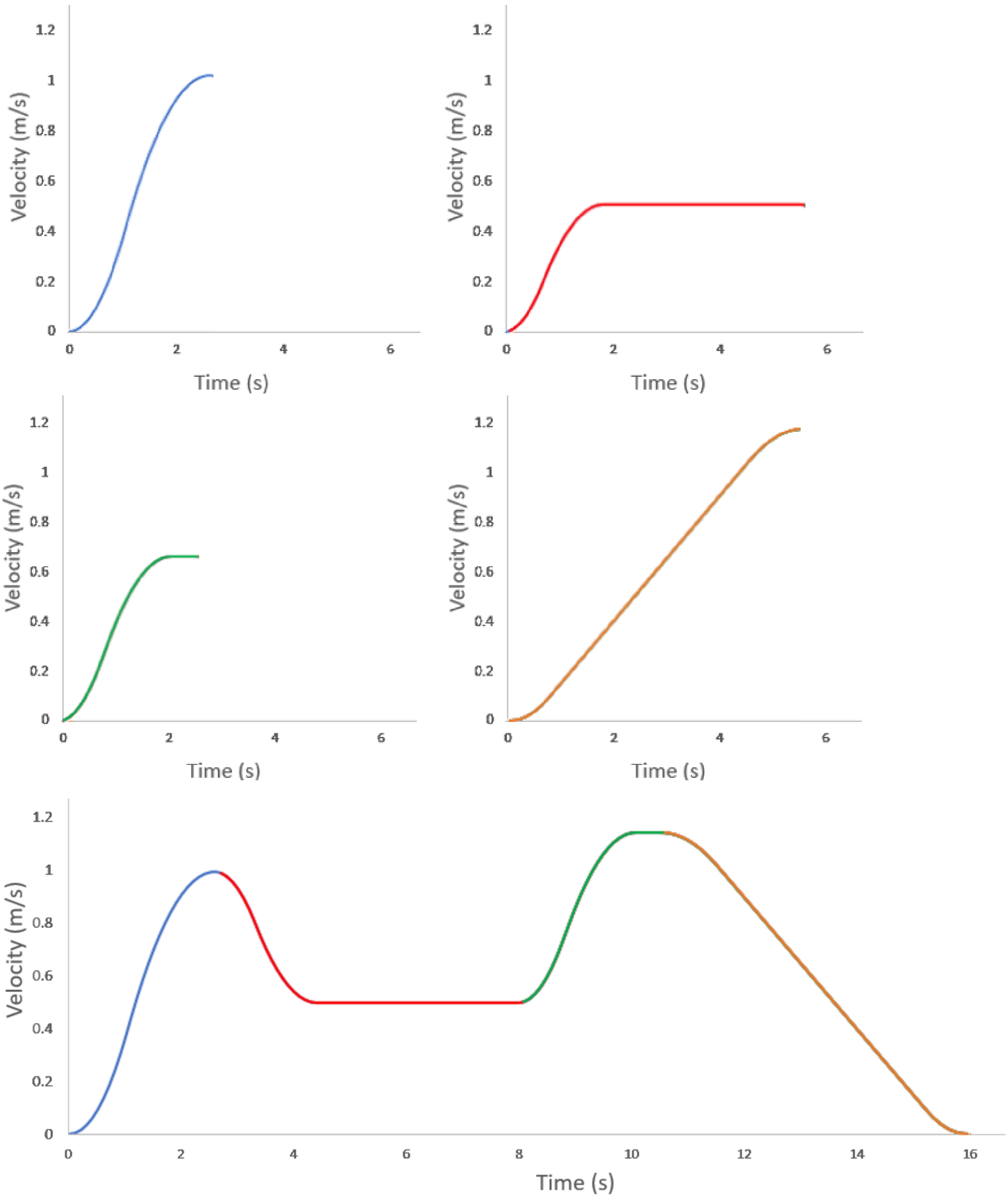

Figure 7 Dynamic phases

In the asymmetric profile, the two phases can be calculated separately and then appended to the same profile later. This is essential for modelling dynamic profiles as seen in Figure 7. Each phase has been plotted on a separate graph and then manipulated and appended to make the final profile.

For more detail on the method, please read "Dynamic extension for Ideal Kinematics" [3] which explains the functionality of the code, provides the necessary equations and shows some examples of the profiles the code generates.

4 QUICKEST STOP FLOOR

4.1 The problem

The quickest stop floor is the next floor a travelling lift can stop at when a new call is made. This is not necessarily the next floor that the lift passes after the call comes in as the car's velocity might be too high to come to a stop in time.

In a symmetric system, this is easy to find with some straightforward equations as seen in [6]. These equations assume condition A, B or C and then reverse the equation for finding the time of max velocity into an equation for the minimum displacement. In the asymmetric model, condition B and C are amended into condition A by reducing the velocity or the acceleration. This means a new approach is needed to find the minimum displacement for asymmetric and dynamic profiles.

4.2 The solution

When using the dynamic model of kinematics, displacement cannot be found using one equation, but instead a function is required which acts recursively to find the displacement at the end of each phase. To find the minimum displacement, this function must be fed with the maximum allowed acceleration and jerk values as well as the lowest possible velocity in the final phase. To find the minimum displacement, the minimum possible velocity must be found.

4.2.1 In period 0

The lift car is currently jerking towards its target acceleration. The acceleration when the call was received is the new target acceleration and the time of the call is set as period 1 and 2 start time. Period 3 start time is then calculated by finding the time taken to reduce the acceleration to zero. The maximum velocity is then calculated by rearranging the period 3 equation.

$$v = a_1\left(p_3 - \frac{a_1(j_1 - j_2)}{-2j_1j_2} - p_0\right) \tag{1}$$

4.2.2 In period 1

The lift car is travelling at a constant acceleration. The time of the call is set as period 2 start time. Period 3 start time is then calculated by finding the time taken to reduce the acceleration to zero. The maximum velocity is then calculated using equation 1.

4.2.3 In period 2

The lift car is currently returning to zero acceleration so the velocity which is currently being targeted is the lowest target velocity possible.

4.2.4 In period 3

The lift car is at constant velocity, so the target velocity is already achieved. The final phase can begin at the same time as the call is sent and the minimum displacement can be found.

5 APPLICATION

5.1 More accurate lift traffic analysis

When modelling lift kinematics, it is currently assumed that the acceleration is the same as the deceleration and that all four jerk values are the same. In a real lift system, due to old or inexpensive mechanics, acceleration and deceleration can vary in a single journey. This can be measured by a car mounted accelerometer and analysed to make a more accurate simulation of an existing system. To use this asymmetric data, equations which model asymmetric lifts must be used.

5.2 Lift systems with two cars per shaft

When two cars share a shaft, the system performance can be improved by giving each car the option to follow a deliberate asymmetric profile thus improving the performance of the system [2].

5.3 Multi-dimensional lift system

For multi-dimensional systems, cars can be given the option to change velocity based on the location of other cars in the system. This can prevent unnecessary stops, improving user experience, and can reduce waiting times, improving performance.

5.4 Improvements to monitoring

Lift performance measurement tools [7] currently try to map the lift's motion to a symmetric profile. Not only will this new model allow monitoring of deliberately asymmetric lifts, data from which will improve simulation inputs, it will also allow for the monitoring of poorly adjusted symmetric lifts thus enhancing maintenance.

6 CONCLUSION

This paper provides a high-level understanding of the dynamic model for plotting kinematic profiles. It explains the basic logic behind splitting a profile into phases and how this can be useful for monitoring, simulating and dispatching.

7 ACKNOWLEDGEMENTS

The authors acknowledge the work of Dr Gabrielle Anderson (formerly of Peters Research Ltd) and her research into the field of lift kinematics with multiple maximum velocities and with separate acceleration and deceleration.

REFERENCES

[1] R. Peters, "Ideal Lift Kinematics," in *Proceedings of ELEVCON '95*, Hong Kong, 1995.

[2] S. Gerstenmeyer, Quality and quantity of service in lift groups, University of Northampton, 2018.

[3] M. Appleby and R. Peters, "Dynamic extension for Ideal Kinematics," *Transportation Systems in Buildings,* vol. 4, 2022.

[4] CIBSE, CIBSE Guide D: Transportation systems in buildings, 2020.

[5] T. Croft, Mathematics for engineers, Pearson Prentice Hall, 2015.

[6] R. D. Peters, " Ideal Lift Kinematics: Derivation of Formulae for the Equations of Motion of a Lift," *International Journal of Elevator Engineers,,* vol. 1, no. 1, 1996.

[7] R. Peters, "Lift Performance Time," in Proceedings of the 2nd Symposium on Lift and Escalator Technologies, Northampton, 2012.

BIOGRAPHY

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Design-Operation Continuum Methods for Traffic Master

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Keywords: DevOps, Traffic Master, Dispatching Algorithms.

Abstract. The lifecycle of lifts could last up to 30 years. As with any other electrical or mechanical component, software of lifts also requires a maintenance process. Maintenance copes with (1) hardware obsolescence and/or degradation, (2) bug fixing, (3) new functionalities, (4) requirements changes, etc. This evolution requires reliable and automatic engineering methods for developing and operating lifts. Advances in the last few years have resulted in a more efficient development process, improving modelling and simulation techniques to validate complex systems from the early phases of development. However, once the system is deployed, methods used during operation and maintenance do not have synergies with methods used during the design. The steps from the development to operation, i.e. testing, delivery and deployment, often require certain manual work to guarantee reliability. Current software development approaches are not applicable or require extension for lifts, where evolution is constant. Furthermore, learning from operational data to enhance the design is becoming a necessity in this sector.

The ADEPTNESS project seeks to investigate and implement a streamlined and automatic workflow that makes methods and tools for the software development and maintenance of lifts to be seamlessly used during design phases as well as in operation. The ADEPTNESS framework uses a novel embedded microservices-based architecture for the context of lifts. The generation and reuse of test cases and oracles from initial phases of the development to the system in operation and back to the laboratory for further analysis will be investigated. This will guarantee a faster and more reliable detection of faults before a new software release is deployed into the lift installations. This deployment will be automatic and synchronised to improve the agility of the whole workflow that covers design-operation continuum. Additionally, test oracles will run both at design-time as well as at operation, permitting the continuous validation of a software release.

1 INTRODUCTION

The traffic master and its software are one of the core components of a system of lifts. As other components, its software requires maintenance over years to deal with different aspects like bugs or problems that arise in operation (e.g., unforeseen situations). While in other types of systems (e.g., web systems) design operation continuum methods like DevOps have emerged, in complex systems like lifts, where the software is embedded and needs to interact with physical components, such methods pose several challenges.

The Adeptness H2020 project is a project that aims at adapting DevOps methods to the context of Cyber-Physical Systems. Specifically, to validate such methods, one of the use-case encompasses the traffic master of Orona's lifts. In this paper, we summarize the methods we developed and instantiated in the context of lifts. Specifically, we instantiate the reference architecture based on embedded microservices in the use-case to allow for design-operation methods. In addition, we carry out an analysis of the benefits this would pose.

2 ARCHITECTURE OF EMBEDDED MICROSERVICES FOR DEVOPS OF TRAFFIC MASTER

2.1 Architecture definition methodology

The first step when designing the architecture based on embedded microservices was to define a methodology for the architecture definition. This methodology consisted of six main steps [1]:

1. Use-case definition: Use-case scenarios were defined by domain experts from the lift industry. These can be found in [2].
2. Stakeholder requirements: By considering these scenarios, we elicited a set of requirements for the architecture, which can be found in [3].
3. DevOps toolchain requirements elicitation: System requirements and subsystems requirements were elicited by having as input the stakeholder's requirements, accessible in [3].
4. Requirements analysis and microservice identification: A system architect performed the first analysis with the elicited requirements and a set of microservices was identified.
5. Interface identification: The different interfaces were defined and integrated with one microservice template developed during the Adeptnes H2020 project. This template is available both in C and Python.
6. Instantiation: Lastly, the different templates were intanted and integrated

2.2 Microservices-based architecture for DevOps of the traffic master

Figure 1 shows an overview of the proposed microservice-based architecture. The architecture contains microservices at two computational levels: (1) the cloud and (2) the fog, i.e., a local network close to the lift. The architecture can be divided into four main subsystems: (1) the automation server, (2) the deployment subsystem, (3) the monitoring subsystem and (4) the validation subsystem.

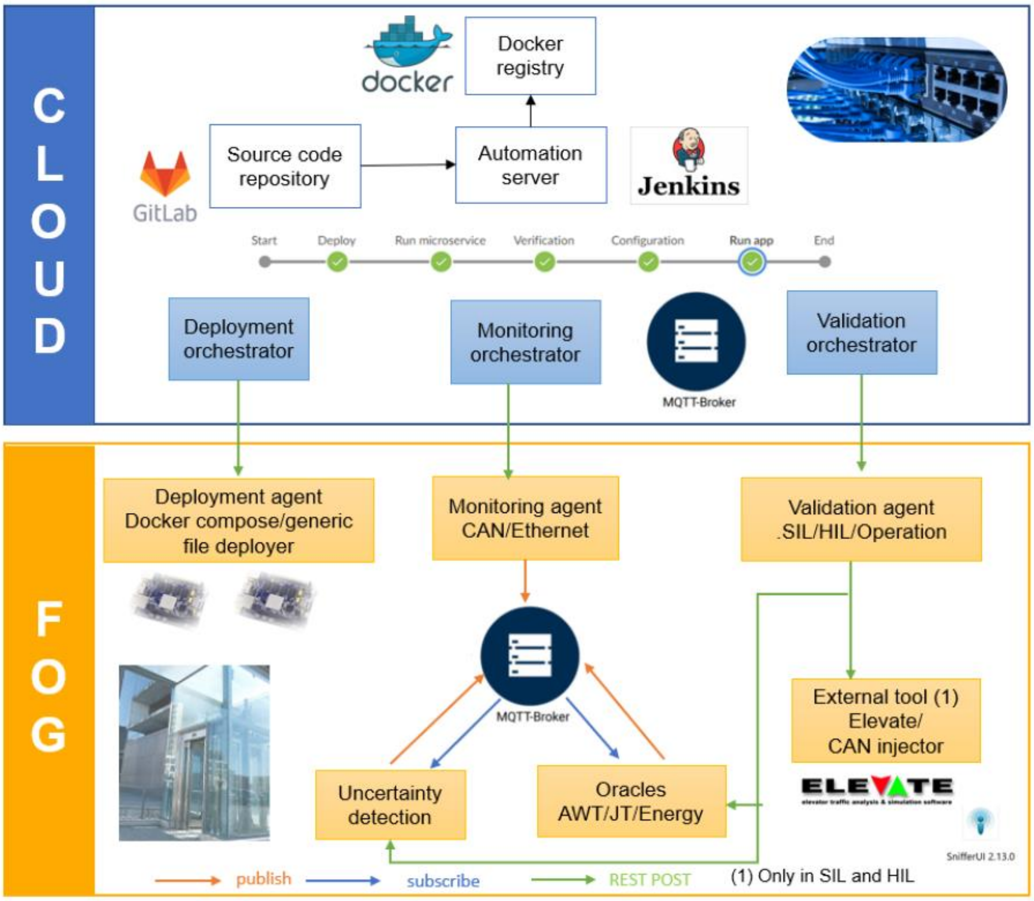

Figure 1 Overview of the architecture for DevOps of the Traffic Master

Common microservices interfaces

All the microservices have certain common interfaces to allow for communication among them. This communication can be either synchronous or asynchronous. For synchronous communication, we used REST communication whereas for asynchronous we used MQTT.

The following interfaces are common for Synchronous communication via REST:

- /adms/v1/ping [GET]: Ping service to check that the service is alive. Returns an empty 200 response if the microservice is working correctly.
- /adms/v1/info [GET]: Provides basic information about the microservice. It returns a JSON object containing the microservice ID and microservice role within the architecture.
- /adms/v1/performance [GET]: Provides CPU and memory usage metrics. It returns a JSON object containing the free and allocated memory and the CPU usage.
- /adms/v1/status [GET, PUT]: Permits getting or changing the execution status of the microservice. GET calls to this endpoint will return a JSON object containing the status of the microservice. Changes to the microservice status will be performed by sending a JSON object with the desired state. The possible states for the microservice are “Ready” and “Running”.

For asynchronous communication, the following interfaces are common to all microservices, which communicate through MQTT:

- /adms/v1/discovery [PUB]: On microservice launch, the microservice publishes a hello message in this topic including the identifier, microservice role and its MQTT and REST endpoints, defined as a JSON object.

The automation server:

When developers propose a change in the code, this is committed to a GitLab repository. In such a repository, an automation server based on Jenkins orchestrates different jobs, including a verification phase where different test executions are performed by following advanced techniques like metamorphic testing [4], uncertainty-wise testing [5] and machine-learning based techniques [6]. Such tests are carried out either at the Software-in-the-Loop (SiL) test level, or the Hardware-in-the-Loop (HiL) test level. The former is a simulation-based testing method where Elevate is used as the core simulator. The latter refers to a real-time emulation where most of the hardware of the system is real, while the mechanical and electrical parts are emulated with real-time infrastructure. When all verification activities are finished and all tests pass, the automation server triggers the deployment microservice to deploy the new software version in the required installations.

Deployment subsystem:

The deployment subsystem is in charge of downloading, decompressing and executing different microservice artifacts, including the new dispatching algorithm versions, on the edge. It is composed on two different microservices: (1) the deployment microservice and (2) the deployment agent. The former receives a plan for deployment triggered by the automation server. The core task is to send these deployment instructions to the different deployment agents installed in each node (i.e., lifts installations across the globe). The latter is a microservice that is installed in each edge node to perform the actual deployment. Two different types of components can be deployed: (1) a docker-compose based deployer that deploys docker containers and (2) a generic deployer to deploy any kind of files. This way, the deployment agent has a high flexibility.

Monitoring subsystem:

This subsystem configures different monitors based on a monitoring plan, which provides telemetry data from different sources (e.g., dispatching algorithm or the main bus). Two microservices are considered: (1) monitoring orchestrator and (2) monitoring agent. The former parses the monitoring plan triggered from the automation server and configures all the monitoring agents. The latter is deployed in the edge and is responsible for reading the operational variables from different sources and publishing them asynchronously through MQTT. Two main monitors are used in the case study. On the one hand, the CAN monitor, which allows for monitoring operational data shared through the CAN bus. On the other hand, the instrumented code monitor, which allows for monitoring data from instrumented code. All this data is published using the SenML [7] format.

Validation subsystem:

The validation subsystem supports the verification of new traffic master versions at different test levels, including (1) SiL, through the use of Elevate, (2) HiL and Operation. It is composed of five different microservices. The validation orchestrator microservice is located in the cloud and manages the execution of a validation plan. The validation agents are located in the fog and launch validations at the SiL and HiL test levels. The oracle microservice receives inputs and outputs of the system under test and provide test verdicts (i.e., pass, fail or inconclusive). The uncertainty microservice works similarly to the oracle microservice but aim at detecting unforeseen situations (e.g., ghost passengers, wrong behavior of the user). Lastly, the external tool microservice provides a communication link with external tools like Elevate.

3 EXPECTED BENEFITS

We prototyped these DevOps methods with the traffic master of our lifts. A video of the full prototype can be viewed in the following link: https://youtu.be/uoq9n9k4kgc

Based on this prototype, we carried out an evaluation to assess which are the core benefits of using DevOps practices to develop new traffic master versions. The expected main benefits for each subsystem can be summarized as follows [1]:

- Deployment subsystem: The main expected benefit is the need for not requiring manual intervention when deploying the software releases, and having full control over the configuration of the release.
- Monitoring subsystem: It will reduce the effort of analyzing problems in lifts' installations and enable continuous remote monitoring.
- Validation subsystem: It provides systematic and advanced testing methods that will enable increasing the number of bugs detected before releasing a new traffic master version. Furthermore, it will enable continuously testing of new releases not only at design-time but also at operation, enabling the possibility of rolling back to a previous version when the new traffic master version is faulty.

4 CONCLUSION

In this paper, we propose the instantiation of a reference architecture based on microservices to support the design-operation continuum engineering of our lift traffic master. This reference architecture has been proposed in the Adeptness H2020 project. Future work includes a comprehensive evaluation of the methods and a thorough cost-benefit analysis of using these methods.

REFERENCES

[1] Gartziandia, A., Ayerdi, J., Arrieta, A., Ali, S., Yue, T., Agirre, A., ... & Arratibel, M. (2021, March). Microservices for Continuous Deployment, Monitoring and Validation in Cyber-Physical Systems: an Industrial Case Study for Elevators Systems. In 2021 IEEE 18th International Conference on Software Architecture Companion (ICSA-C) (pp. 46-53). IEEE.

[2] Requirements-and-validation-tests – https://adeptness.eu/wp-content/uploads/2020/09/D1.1-ANNEX-A-Requirements-and-validation-tests.pdf

[3] Requirements-and-validation-tests – https://adeptness.eu/wp-content/uploads/2020/11/D1.1-REQUIREMENTS_v1.1.pdf

[4] Ayerdi, J., Segura, S., Arrieta, A., Sagardui, G., & Arratibel, M. (2020, October). Qos-aware metamorphic testing: An elevation case study. In 2020 IEEE 31st International Symposium on Software Reliability Engineering (ISSRE) (pp. 104-114). IEEE.

[5] Galarraga, J., Marcos, A. A., Ali, S., Sagardui, G., & Arratibel, M. (2021, October). Genetic Algorithm-based Testing of Industrial Elevators under Passenger Uncertainty. In 2021 IEEE International Symposium on Software Reliability Engineering Workshops (ISSREW) (pp. 353-358). IEEE.

[6] Arrieta, A., Ayerdi, J., Illarramendi, M., Agirre, A., Sagardui, G., & Arratibel, M. (2021, May). Using machine learning to build test oracles: an industrial case study on elevators dispatching algorithms. In 2021 IEEE/ACM International Conference on Automation of Software Test (AST) (pp. 30-39). IEEE.

[7] SENML format – https://tools.ietf.org/html/rfc8428

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BIOGRAPHICAL DETAILS

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Dr. Aitor Agirre: He is a senior researcher at Ikerlan research center. Currently he is involved in the Adeptness H2020 project and also in transfer projects with Orona.

Dr. Goiuria Sagardui: She is the coordinator of continuous education at Mondragon University, and she is also a researcher working in both research projects and transfer projects, especially with Orona.

Maite Arratibel: She is a senior engineer in Orona, who coordinates the research and development of the traffic master. Before, she worked as an engineer in Ikerlan.

Rated Load and Maximum Available Car Area
A Proposal to Revise EN81-20, Table 6

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Keywords: rated load, car area, EN81-20, passenger area, traffic design

Abstract. In the USA during the 1920s, concerns were expressed that large lifts were being overloaded owing to the lift attendants in the cars pushing passengers into their cars. On group systems this was aggravated by the human despatchers forcing passengers into the cars. The result was the density of the passenger load increased as the cars got bigger. Non-domestic buildings were designed in the USA for a uniformly distributed load of 60 pound per square foot (psf) on open areas of building floors and this was used for lift car floors. To ensure passenger safety the load bearing was increased to 100psf for lifts carrying 10,000lb (A17.1:1925), and in 1937 to 127.5psf (A17.1:1937) for lifts carrying 37,500lb. This resulted in a nonlinear relationship between passenger load and the available car area on which they stand. This can be seen in Table 6 of BS EN81-20:2020/BS ISO8100-1:2019.

NOTE 1: Whenever EN81-20 is referred to in this paper it means: BS EN81-20:2020/BS ISO8100-1:2019

Societal changes, where individuals do not tolerate the discomfort of other individuals intruding into their personal space; and technological advances in load weighing, demands a reconsideration of the space a passenger occupies and its corresponding rated load. A proposal to revise the relevant standards is presented.

The concept of a Body Area Index is introduced to allow for a wide range of body weights across the world.

NOTE 2: Imperial measures are referred to and these may be converted as one pound (lb) = 0.454 kg and one square foot (sf) = 0.093 m^2.

1 BASIC TRAFFIC DESIGN

When lift traffic designers size a lift installation to meet a specific passenger demand (say, 12% of the likely building population), at a defined performance level (say, providing an interval of 25 seconds), the lift traffic designer specifies the number of lifts, their rated speed, door times, etc. AND the average number of passengers (P) to be transported on each trip.

Passengers do not conveniently arrive in batches of P passengers, but randomly. The lift traffic designer accommodates this statistical variation by estimating the maximum number of passengers (P_{max}) to be transported to be:

$$P_{max} = \frac{P}{0.8} \qquad (1)$$

This is the maximum number of passengers to be accommodated. But what is the rated load?

NOTE 3: Equation (1) contains the denominator 0.8, that means that P is taken as 80% of $Pmax$. The 80% estimation is a common statistical adjustment.

Inside each lift car there is a rating plate, which states the rated load (Q) in kg. It often also states the maximum number of passengers that can be safely transported according to the formula in clause 5.4.2.3.1a), BS EN81-20:2020 [1] or BS ISO 8100-1:2019 [2]:

$$P_{max} = \frac{Q}{75} \tag{2}$$

and the result rounded down to the nearest whole number.

NOTE 4: In Equation (2) the denominator figure of 75 assumes that the average passenger weight is 75kg.

The rated load (kg) is $75P_{max}$. For example, P_{max} is 17 persons, then the rated load is 1275kg.

2 THE RATIONALE IN THE CHOICE OF THE 75kg PER PASSENGER

The rationale for the choice of 75kg is hidden in American standards as far back as 1925.

A graph was published (shown here as Figure 1) in the US ANSI A17.1: 1925 *Safety code for elevators*. [3]

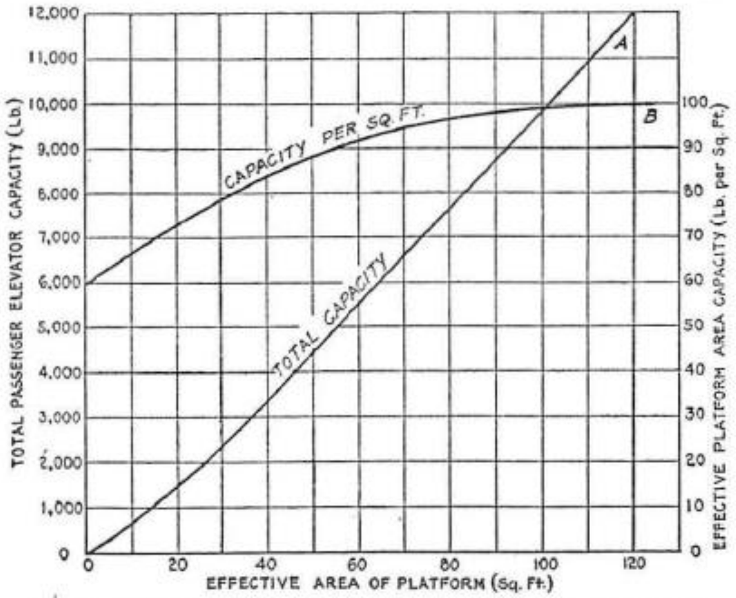

FIG. 4 PLOT SHOWING PASSENGER-ELEVATOR CARRYING CAPACITY CORRESPONDING TO EFFECTIVE PLATFORM AREA

NOTE: For passenger elevators having effective platform areas above 120 sq ft the contract load shall be not less than 100 lb per sq ft.

Figure 1: Figure 4 from A17.1:1925

Curve A on this graph shows the rated passenger capacity (load) in pounds (lb) [left y-axis] for a range of effective car platform areas in square feet (ft^2) [x-axis]. Curve B shows load (lb) per ft^2 (psf) [right y-axis]. Note this is nonlinear. The same graph is published in the A17.1:1931.

In July 1935, the UK Building Industries National Council published a *Code of Practice for Electric Passenger & Goods Lifts and Escalators* [4]. In it they stated:

> *c) A plate shall be affixed to each lift car in a conspicuous position and shall bear at least the following particulars: -*
>
> *(i) The contract load of (goods) lift in cwts. and/ or lbs.*
>
> *(ii) The maximum capacity of (passenger) lift in passengers, calculated at 150 lbs. per passenger.*

There was no supporting graph and no indication of the car platform area. But it implies the assumption an average passenger weighs 150lb. A17.1:1937 [5] provides the graph of 1925 and assumes a passenger weighs 150lb (Rule 217c) supporting the British view.

In May 1943, the UK Building Industries National Council revised their 1935 COP [6] to include a graph, shown here as Figure 2. This graph is clearly based on the US ANSI A17.1: 1925 (Figure 1) but rationalised to suggest a $50ft^2$/5000lb pairing rather than the $50ft^2$/4400lb. The ANSI A17.1:1945 [7] adopted this rationalisation.

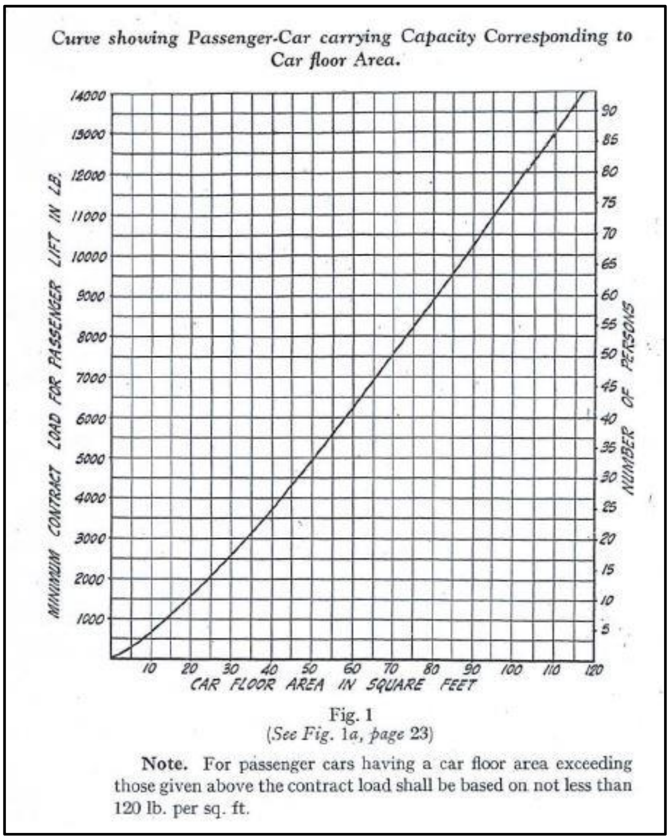

Figure 2 Extract for 1943 Code of Practice

Why is the curve not linear? This is due to Curve B of Figure 1, which shows the lift car floor loading increases from 60psf to 100psf. Why is this?

It was the custom in the 1920s/1930s for lifts to have an attendant to drive the lift. Where there was a lift group, often there was a (human) despatcher on the landing forcing passengers into the cars. These two persons had the function to squeeze as many people as possible in a lift before it was despatched. This led to the observation that the density of passengers increased as the cars got larger. Curve B was the solution. It shows the car floor loading increases from 60psf to 100psf (and later higher to 127.5psf). That is more passengers per square foot!

Another factor was there were no reliable load weighing devices to stop lifts starting up in an overload condition.

This imposed nonlinearity coped with possible overloading at that time as there is a limit to how many people can be squeezed into a small space.

Versions of this graph were included in BS2655, Part 1:1958 [8] and 1970 [9].

By 1955 A17.1 had equations to represent the curves in Figure 2, see PD ISO/TR11071-2:2006, Table 11 [10].

The curve had a discontinuity at available car areas (Ac) above 5m^2/50ft^2. This was a pragmatic point as very few passenger lifts had rated loads greater than 2500kg/5000lb. Lifts up to this point followed a quadratic equation (3).

Up to 5m^2 use Equation (3):

$$Q=35.05Ac^2+325.7Ac \tag{3}$$

After the discontinuity point, A17.1 continued with a different quadratic equation (4A), but CEN used a linear equation (4B).

A17.1 used

$$Q = 2.454Ac^2 + 610.3Ac - 620.1 \tag{4A}$$

CEN standards uses a linear equation.

$$Q = 625(Ac - 1) \tag{4B}$$

NOTE 5: In Equations (3), (4A) and (4B) the variable Ac is in m^2.

Curves are difficult to read and the BS 5655-1:1986/EN81-1:1985 [11] standards used these equations and produced Table 1.1 for a number of rated load values. Table 6 in both EN81-20:2020 and ISO 8100-1:2019 are identical to Table 1.1. Table 1 below shows an extract of common rated loads from EN81-20:2020 plus the ISO recommended rated load of 1800kg, which is missing from Table 6.

Table 1: Extracts from Table 6, EN81-20:2020

Rated load (Q) (kg)	Maximum available car area (A_c) (m^2)
450	1.30
630	1.66
800	2.00
1000	2.40
1275	2.95
1600	3.56
1800	3.88
2000	4.20
2500	5.00 (c)
(c) Increases by 0.16m^2 for each extra 100kg	

3 CURRENT SPACE PER PASSENGER

Consider Table 2.

The third column has been added to Table 1 to show the rated number of passengers (rounded down), weighing 75kg each according to Equation (2). This is the number the in-car rating plate displays. The fourth column has been added to show the space that each passenger is allocated to occupy. Notice the diminishing space per passenger.

Table 2: Space per passenger according to EN81-20:2020, Table 6

Rated load (Q) (kg)	Maximum available car area (A_c) (m²)	Rated passengers (P_{max})	Space per passenger (m²)
450	1.30	6	0.22
630	1.66	8	0.21
800	2.00	10	0.20
1000	2.40	13	0.18
1275	2.95	17	0.17
1600	3.56	21	0.17
1800	3.88	24	0.16
2000	4.20	26	0.16
2500	5.00 (c)	33	0.15
NOTE 6: Passenger figures are rounded down.			

The passengers in a 450kg car have a personal space of 0.22m^2 (1.30/6), but the passengers in a 2500kg car have a personal space of 0.15m^2 (5.00/33). As passengers board a large lift car they eventually begin to intrude into other passengers' personal space (shown dashed in Figure 3). Eventually there is no space left and intimate body to body contact occurs (shown solid line in Figure 3). It reaches the crush situations that are seen on subway systems, such as the London Underground. Lift passengers do not tolerate this and are uncomfortable and refuse to board.

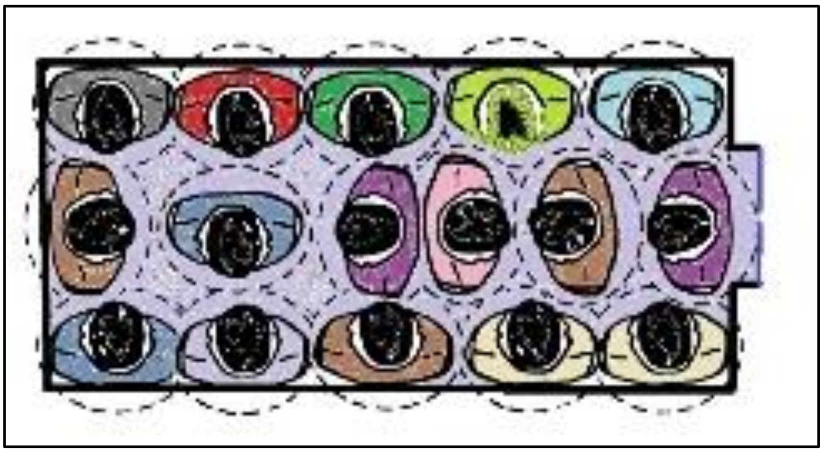

Figure 3 Room for one more?

NOTE 7: Illustrates a 1275kg car with 16 passengers – the in-car rating plate indicated 17 passengers. The average body ellipse is assumed to be 0.21m^2 at 75kg/passenger.

This confirms there is not enough room in the car for the average sized passengers.

Observations made by this author and others since 1990 noted that lift cars do not fill to the number of passengers indicated on the in-car rating plate and conclude it cannot be relied upon for traffic design. This is because passengers do not like the discomfort of their personal space being violated. There are exceptions where passengers have a strong motivation to sacrifice comfort: a group of passengers travelling together may "squash in"; passengers with an urgent need to travel; a student prank.

Leenders in his analysis of EN81-1:1985/BS5655-1:1986 [12] writing in 1986 says

"Laboratory experiences conducted in the States half a century ago indicated people could squeeze themselves into a car up to 32% overload and that 42% could even be reached but I suspect that it needed some exterior help as in the Japanese subway".

An expert writing in PD ISO/TR11071-2:1996 [10] opines:

8.2.1 While the entire subject of capacity and loading has historically been treated in safety codes as one and the same, it might be more meaningful in the future writing of safety codes to cover {1} *loading as a separate issue from* {2} *capacity. One* {2} *refers more appropriately to the traffic-handling capability, whereas the other* {1} *refers to the maximum carrying capacity, which has a direct bearing on safety.*

The conclusion is passengers need more space.

4 PROPOSED SPACE PER PASSENGER

Using work by Fruin [13] and others, this author suggested in CIBSE Guide D:1993 [14] that the "standing area" for a person weighing 75kg should be 0.21m^2. This is the area of Fruin's body ellipse of 600mm by 450mm and scales up from the original assumption of a person weighing 150lb standing on two square feet.

The average passenger area of 0.21m^2 is now quoted and used extensively, see ISO 8100-32:2020 [17].

Applying this space requirement, the car area for a 33-person car should be 6.93m^2. A range of necessary available car areas are shown in Table 3.

Table 3: Proposed revision of EN81-20, Table 6 for traction and hydraulic lifts

Rated load Mass (Q) (kg)	Maximum available car area (A_c) (m^2)	Maximum number of passengers (P_{max})	Average number of passengers (P)
450	1.26	6.0	4.8
630	1.76	8.4	6.7
800	2.24	10.7	8.6
1000	2.80	13.3	10.6
1275	3.57	17.0	13.6
1600	4.48	21.3	17.0
1800	5.04	24.0	19.2
2000	5.60	26.7	21.4
2500	7.00	33.3	26.6
3000	8.40	40.0	32.0
4000	11.20	53.3	42.6
5000	14.00	66.7	53.4
10000	28.00	133.3	106.6
15000	42.00	200.0	160.0
20000	56.00	266.7	213.4
Beyond 20000 kg, add 0.21 m^2 for each extra 75 kg/0.28 m^2 for each extra 100 kg. For intermediate areas, the rated load can be determined by 360 × A_c. All passengers have an average weight of 75kg Numbers of passengers are average values and are decimal			

NOTE 8: A wider range of values can be found in Table (5).

NOTE 9: The maximum number of passengers is shown as a decimal value and for practical purposes would be rounded down.

What is being suggested here is that the maximum area available for a specific rated load should be increased to accommodate the size of passengers, not what they weigh. The nonlinearity of available car area/rated load ratio is removed. The lift traffic designer has a realistic value for maximum car occupancy.

A similar concept was made available for hydraulic lifts, see Table 7 of EN81-20:2020. The argument supporting this concession can be found in PD ISO/TR11071-2:1996.

5 SAFETY

Passenger safety is paramount.

EN81-20:2020 Table 6 increases the live loading from 350kg/m^2 for small cars (eg: rated load 450kg) to 500kg/m^2 for large cars (eg: rated load 2500kg). This is illogical for lifts – it should be linear.

In **Table 3** the rated load is the prime parameter, and the lift components shall be designed for the stated rated load. With modern load weighing devices (not available in the 1920s/1930s) a lift will not start if it is overloaded, by for example, the presence of too many passengers or heavy goods. This safety provision is supported by the other (and less obvious) safety requirements in EN81-20 that the braking and traction components shall withstand excess loads of 125% rated load. In practice, a lift only <u>ever</u> carries the rated, and 125% rated loads, when under test.

Table 4: Proposal to revise Table 6, EN81-20 – a larger range of values

Rated load Mass (Q) (kg)	Maximum available car area (A_c) (m^2)	Maximum number of passengers (P_{max})	Average number of passengers (P)	Rated load Mass (Q) (kg)	Maximum available car area (A_c) (m^2)	Maximum number of passengers (P_{max})	Average number of passengers (P)
100 (a)	0.37	1.8	1.0	1350	3.78	18.0	14.4
180 (b)	0.58	2.8	2.0	1425	3.99	19.0	15.2
225	0.63	3.0	-	1500	4.20	20.0	16.0
300	0.84	4.0	-	1600	4.48	21.3	17.0
375	1.05	5.0	-	1800	5.04	24.0	19.2
400	1.12	5.3	-	2000	5.60	26.7	21.4
450	1.26	6.0	4.8	2500	7.00	33.3	26.6
525	1.47	7.0	5.6	3000	8.40	40.0	32.0
600	1.68	8.0	6.4	3500	9.80	46.7	37.4
630	1.76	8.4	6.7	4000	11.20	53.3	42.6
675	1.89	9.0	7.2	4500	12.60	60.0	48.0
750	2.10	10.0	8.0	5000	14.00	66.7	53.4
800	2.24	10.7	8.6	6000	16.80	80.0	64.0
825	2.31	11.0	8.8	7000	19.60	93.3	74.6
900	2.52	12.0	9.6	8000	22.40	106.7	85.4
975	2.73	13.0	10.4	9000	25.20	120.0	96.0
1000	2.80	13.3	10.6	10000	28.00	133.3	106.6
1050	2.94	14.0	11.2	15000	42.00	200.0	160.0
1125	3.15	15.0	12.0	20000	56.00	266.7	213.4
1275	3.57	17.0	13.6	30000 (c)	84.00	400.0	320.0
	a Minimum for 1 person lift (unchanged). b Minimum for 2 persons lift (unchanged). c Beyond 30000 kg, add 0.21 m^2 for each extra 75 kg/0.28 m^2 for each extra 100 kg. For intermediate loads, the area is determined by linear interpolation. All passengers have an average weight of 75kg Numbers of passengers are average values and are decimal						

6 A PROPOSAL FOR CHANGE

For a range of rated loads, Table 2 shows the maximum number of passengers permitted based on 75kg per passenger and the maximum available car area required based on 0.21m^2 per passenger is shown in Table 3. The commonly available rated loads are shown.

For consistency and clarity EN81-20 hydraulic lifts should also follow **Table 3** and EN81-20, Table 7 can then be deleted. Alternatively, as hydraulic lifts have other safety measures to avoid overload the concession of the extra floor area could still be included if desired.

As passenger numbers are now shown in Table 3, then EN81-20, Table 8 can also be deleted.

In simple terms the rated load is given in Table 3 as 360 multiplied by the available car area on the basis of live load intensity of 360kg/m^2.

A consequence of this proposal to transport more people in the larger lift cars, is energy can be saved and embodied carbon reduced as lifts will be selected with a lower rated load due to the larger available car area for passengers.

7 EXAMPLE 1

A lift with an available car area of 3.47m^2 is to be modernised.

A traffic designer determines the average number of passengers to be carried as 13.6. From Table 3 a lift with a rated load of 1275kg would be selected. The available car area is 3.57m^2.

What will the new rated load be and how many passengers can be transported?

With an area of 3.47m^2 then interpolating Table 3 the lift should have a rated load of 1240kg. It can then transport a maximum of 16.5 passengers and on average 13.2 passengers. This is smaller than required. As traffic design is not an exact science, in practice a lift with a rated of 1275kg would be selected.

8 IN SUMMARY

The car loading to effective (available) car platform area ratio started in the 1920s as a linear value at 60lb/ft^2, but as overloading was feared the ratio became nonlinear and was increased for larger cars to 127.5lb/ft^2 by the 1980s. It has remained so ever since as EN81-20, Table 6.

For a range of rated loads, Table 2 (extracted from Table 6) shows the maximum number of passengers permitted based on 75kg per passenger, but with reducing available car areas as the rated load increases.

EN 81-20, Table 6 shall be revised to reflect the reality of the 2020s bringing the elegance of the 1920s into the 2020s.

For a range of rated loads, Table 3 shows the car area required based on the maximum number of passengers permitted assuming an area of 0.21m^2 per passenger (360kg/m^2) and the corresponding rated load value (360A_c).

Traffic designers can specify a rated load with the confidence that the required number of passengers can be accommodated.

It may be some time before the standards reflect this proposal. However it can be implemented NOW using the current standards quite safely. A Design Examination Certificate would need to be obtained from an Approved/Notified Body for a deviation from a designated/harmonised standard citing the risk assessment evidence in this paper.

The weight of nations [15] should be considered when selecting a lift's rated load in various countries and regions of the world, see Addendum.

REFERENCES

[1] BS EN 81-20:2020: *Safety rules for the construction and installation of lifts. Lifts for the transport of persons and goods. Passenger and goods passenger lifts*

[2] BS ISO 8100-1:2019: *Lifts for the transport of persons and goods. Safety rules for the construction and installation of passenger and goods passenger lifts*

[3] US ANSI A17.1:1925: *Safety code for elevators*

[4] UK Building Industries National Council Advisory Committee on Building Acts and Byelaws. *Code of Practice for Electric Passenger & Goods Lifts and Escalators*. July 1935

[5] A17.1:1937: *Safety code for elevators*

[6] UK Building Industries National Council Advisory Committee on Building Acts and Byelaws. *Code of Practice for Electric Passenger & Goods Lifts and Escalators*. May 1943

[7] US ANSI A17.1:1945 *Safety code for elevators*

[8] BS 2655-1:1958: *Electric lifts: General requirements*

[9] BS 2655-1:1970: *Specification for lifts, escalators, passenger conveyors and paternosters: General requirements for electric, hydraulic and hand powered lifts*

[10] PD ISO/TR11071-2:1996{/2006} *Comparison of worldwide lift safety standards — Part 2: Hydraulic lifts (elevators) Table 11 — Power Passenger Elevator - Capacity and Loading* {A17.1 Code Rule History}

[11] BS 5655: Part 1:1986/EN81: Part 1: 1985, *Lifts and service lifts. Part 1 Safety rules for the construction and installation of electric lifts*

[12] Leenders, A., *Handbook to EN81-1:1985/BS5655-1:1986.* {private purchase]

[13] Fruin, J.J.: *Pedestrian planning and design*; Elevator World, Mobile, USA, 1971

[14] CIBSE Guide D:1993: *Transportation systems in buildings*

[15] Walpole et al: *The weight of nations: an estimation of adult human biomass*. BMC Public Health 2012 12:439

[16] CIBSE Guide D:2020: *Transportation systems in buildings*

[17] ISO 8100-32:2020 Planning and selection of passenger lifts to be installed in office, hotel, and residential buildings

[18] Barney G.C and Dos Santos S.M. *Improved traffic design methods for lift systems,* Build. Sci Vol 10. pp. 277-285, 1975

BIOGRAPHICAL DETAILS

Dr Gina Barney PhD, MSc, BSc, CEng, FIEE, HonFCIBSE, MAE, Principal of Gina Barney Associates, an independent vertical transportation consultancy, entered the lift industry two months after the 1935 COP and has been helping the lift industry ever since.

She and her research team at Manchester University developed the well-known Round Trip Time equation [18], made available an interactive Lift Simulation Design Suite of programs (PC-LSD and specified Adaptive Call Allocation (ACA). She later became involved in ISO work on energy efficient lift and escalator systems.

She is a member of BSI's lift committee MHE/4 and represents the UK on ISO/TC178/WG6/SG5 on traffic design and ISO/TC178/WG10 on energy efficiency. For more on Gina search "Dr Gina Barney."

ADDENDUM: DO ALL PASSENGERS WEIGH 75 kg?

The previous discussion has calculated the number of passengers in a lift by weight by assuming an average passenger weighs 75kg. This is according to EN81 standards and has now been adopted in ISO8100 standards. Do Europeans weigh on average 75kg? Do passengers all over the world all have an average weight of 75kg?

The absurdity of this statement is obvious.

There are nearly 200 countries in the world. Figure 4 shows the average body weights of adults for 177 countries. This figure is derived from seminal work by Walpole et al, *The weight of nations* (15). **Table 5** gives a selected range

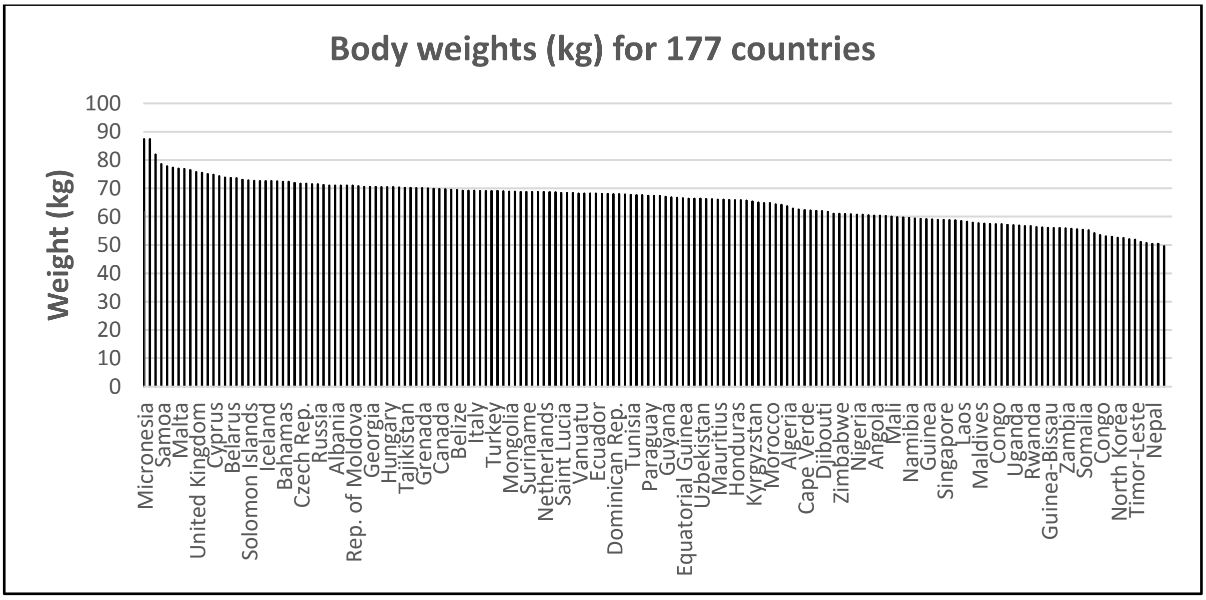

Figure 4 The weight of nations

Source: Walpole et al: The weight of nations: an estimation of adult human biomass. BMC Public Health 2012 12:439. [15]

The adult weight ranges from Bangladesh (50 kg) to Micronesia (87 kg), a 1.74 ratio. The world average is 62kg.

As a 75kg person occupies a space of 0.21m^2 then values for other occupied spaces can be linearly scaled to this body weight, in a similar manner to the BMI (Body Mass Index).

This is termed Body Area Index (BAI). A complete list of these can be found in CIBSE Guide D:2020, Table A2.1 [16] and range from 0.14m^2 to 0.24m^2. The world average is 0.17m^2 based on a world average body weight of 62kg. See Figure 5 for a full range of BAI values.

Table 5 Example range of BAI values.

Country/region	kg	BAI	Country/region	kg	BAI
Tonga	87	0.24	France	67	0.19
North America	82	0.23	China	61	0.17
Australia	77	0.22	Pakistan	59	0.17
Oceania	76	0.21	Singapore	59	0.17
United Kingdom	76	0.21	Africa	59	0.17
Germany	73	0.20	Asia	56	0.16

Russia	71	0.20	India	53	0.15
Switzerland	71	0.20	Vietnam	51	0.14
Europe	71	0.20	Bangladesh	50	0.14
WORLD AVERAGE	62kg		BAI	0.17	

This means a traffic designer who requires, say, an average passenger number of 13.6 persons giving a maximum passenger number of 17 persons would need a bigger lift in Tonga than one in Bangladesh.

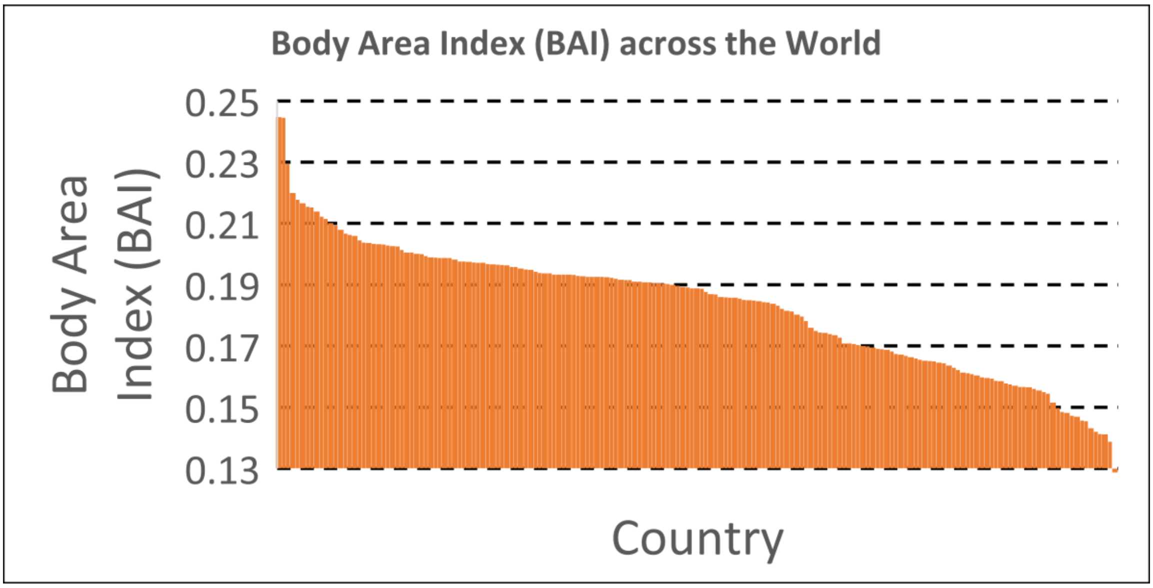

Figure 5: Body Area Index for 177 countries

EXAMPLE 2

Select a lift with a suitable rated load to accommodate a maximum of 17 passengers (a) using EN 81-20, Table 6, shown here as **Table 1**; and (b) using the proposed revision to EN81-20, Table 6 shown here are Table 3.

Table 6: Comparison of questions (a) and (b).

Country	Space required per passenger (m^2)	Total space required (m^2)	Nearest suitable lift rated load/car area (kg (m^2))	
			(a)	(b)
Tonga	0.24	4.08	2000 (4.20)	1600 (4.48)
UK	0.21	3.57	1600 (3.56)	1275 (3.57)
China	0.17	2.89	1275 (2.95)	1000 (2.80) *
Bangladesh	0.14	2.38	1000 (2.40)	1000 (2.24) *
• NOTE 9: These lifts are a few percent smaller than required. An advanced traffic designer would consider other factors and probably specify the next larger available rated load as this will accommodate larger non-domestic residents and visitors.				

Except for the smallest lift in Bangladesh the rated loads are now smaller.

WARNING: Where lifts are installed in countries with BAIs less than 0.21 the lifts may need to be larger if a large number of overseas visitors are expected, eg: an airport.

Global Dispatcher Interface - Initial Prototype Design

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Keywords: Global dispatcher, Standard Elevator Information Schema, group control, prototype, REST, API, UML.

Abstract. This paper presents an overview of the design and development of a prototype Global Dispatcher Interface (GDI) for the control of a group of lifts. The role of the dispatcher is to assign passenger calls to the optimal lift in a group, as decided by a dispatcher algorithm. The GDI is independent of the underlying algorithm, which may be distributed remotely, and provides a standard means through which all interactions with the dispatcher may occur. To warrant the "Global" appellation the GDI must support any of the currently available, as well as anticipated, call station modes, types and configurations of cars, topology of control equipment and buildings. The analysis and design process follows a recognised Systems Development Life-Cycle, centred on Use Cases in a UML model. Significant diagrams from the model are presented and discussed to illustrate the evolution of the prototype design. The requirements, resulting from analysis of the Use Cases, identify that the GDI design must be compatible with a publish-and-subscribe architecture and a RESTful interface is selected for this purpose. Where possible, the prototype design uses open standards with an emphasis on demonstrating those aspects that are specific to lift system dispatcher operation, while attempting to demonstrate independence from implementation details such as programming language, network protocols, etc. The Standard Elevator Information Schema is particularly relevant and fulfils these objectives. The working prototype, which operates in conjunction with simulated lifts and passengers, is presented as a validation of the design.

ABBREVIATIONS USED

API (Application Programming Interface) - a type of software interface, offering a service to other pieces of software.

CoAP (Constrained Application Protocol) - see [22]

GDI (Global Dispatcher Interface) - an interface that separates the lifts and other equipment of a group from the dispatcher in order to present the dispatcher in standard way - the subject of this paper.

JSON (JavaScript Object Notation) - an open standard file format and data interchange format that uses human-readable text. (see - [23])

REST (REpresentaional State Transfer) - A software architectural style (see [17])

SDLC (Systems Development Life-Cycle) - see [4]

SEIS (Standard Elevator Information Schema) - see [13]

UML (Unified Modelling Language) - a general-purpose modeling language in the field of software engineering that is intended to provide a standard way to visualize the design of a system. (see [10])

URI (Uniform Resource Identifier) - a unique sequence of characters that identifies a logical or physical resource used by Internet web technologies. (see [24])

1 INTRODUCTION

While definitions of standard group control algorithms have been documented [1], the reality of group control to date is that manufacturers have created proprietary designs that are inextricably linked to their own lift equipment. The result is that it is not possible accurately to compare or predict the effects on performance of different control policies during the design phase of a building, or in advance of a refurbishment of the lifts. The benefit of a standard interface is that it would make it possible to supply the dispatching capability in a component form that could be "plugged" into any group of lifts that conforms to the interface.

Secondly, a dispatcher design which has been configured and validated using simulation can be transferred directly into a physical installation with confidence, if both the simulator and the real lifts use the same standard interface.

As lifts become better integrated with the other services of so-called "smart buildings" and with the introduction of applications that allow passengers to register requests for lift travel via a variety of channels [2] including personal mobile devices, an interface that allows simplified and standardised secure access to the group call assignment mechanism becomes increasingly desirable.

Furthermore, performance and status monitoring capabilities, possibly added as a later enhancement to an initial lift installation, would benefit from a standard interface, which would be consistent across a number of buildings in, for example, a property portfolio.

A previous paper [3] analysed the requirements for a Global Dispatcher Interface (GDI) via which a group of lifts could be controlled. Current trends and possible future developments in lift group controller technology were reviewed so that the identified requirements are sufficiently broad and flexible to avoid the analysis becoming prematurely outdated. The paper presented a structured statement of the requirements that a GDI must satisfy, followed by an analysis of those requirements using the Requirements Capture and subsequent Analysis phases of a light-weight Systems Development Life-Cycle (SDLC) [4]. The outputs of these initial phases of the process are

- Passenger (user perspective) use cases
- Dispatcher (system perspective) use cases
- Requirements catalogue
- Domain object catalogue (defining roles and responsibilities)

These outputs take the form of a UML Model plus supporting report documentation generated from the model and, because of their number and complexity, are published separately from the paper, which can only present the key features and conclusions. The report documents can be found at the project website [5]. The model has been developed and is maintained via a specialized tool [6] which supports the entire SDLC.

A second paper [7] continues the SDLC process with a discussion of the design and development of a functioning prototype. By definition, a software prototype [8] is not intended to be deployed in a live situation serving real users (i.e. passengers, maintainers, managers, etc.), rather it is intended to demonstrate the viability of delivering a variety of key functional capabilities, while other characteristics may be only partially implemented or completely omitted. Further prototypes may be produced, in order to explore other aspects of the GDI. After each prototype evaluation, the software should be archived and at the conclusion of the final prototype the design and development phases should be completely reiterated, but from that point onwards with the additional requirements of security, performance, robustness and cost fully accounted for in the GDI design.

In addition to the GDI itself, the prototype demonstration system consists of:

- a configurable simulator (a commercial product [9]) of passengers and of lift car activity.
- new gateway software that has been developed to provide a more realistic representation of lift and call registration activity, which in real life (as opposed to in a simulation program) are enacted as independent asynchronous activities.

An important point, presented in [3], relates to the preferred use of open standards to provide the generic hardware and software, which are of themselves not specific to lift systems. Thus the discussion can concentrate on those considerations which are specific to lift systems. In response, the GDI prototype sets out to demonstrate the delivery of dispatching functionality supported by an infrastructure built of as many interoperating, heterogeneous and open technology standards (e.g. programming language, network protocol, etc.) as it is practicable to include.

2 GDI ANALYSIS

The SDLC describes the process by which development should proceed, evolving the requirements use cases into a set of more detailed System Use Cases. During the system analysis phase, a detailed description text of each of the system use cases (the use case "story" or "flow") provides the basis for developing a detailed diagrammatic definition of the sequences of interactions that must occur between the collaborating domain objects. Two principal use cases are identified - Assign Call and Cancel Call - and it is important to understand that in a busy lift system, multiple instances of both these use cases will exist concurrently and all at different stages of completion.

The domain objects have names like "Car" and "Landing Call Device" but represent very general concepts rather than specific items of physical hardware - a level of detail that will not be developed until a later stage. Sequence diagrams elaborate the messages passed between the objects as the use case proceeds. A separate sequence diagram [10] is developed for each significant alternative route ("scenario") [11] through the use case (often the result of different outcomes from an If-Then-Else like decision). For example:

> *"When the assigned car arrives at the call origin floor, if the dispatcher has not been informed of the passenger's destination floor the passenger's call is then deleted from the list of current calls. However, if the destination floor is known then the call is retained but its status is changed to "Answered".*

While there is insufficient space to include all of these sequence diagrams, they are available at [5] and an example (Figure 1) is included for illustration. It is then through the elaboration of sequence diagrams that the design phase of the SDLC can be commenced. During the design phase further sequence diagrams are produced, but now showing the collaborations between the software components which will be implemented, rather than abstract domain objects. This paper is concerned with the design of the Global Dispatcher Interface only but the diagrams also consider the operation of the dispatcher itself to ensure that all of the dispatcher requirements are supported by the interface. The full set of design sequence diagrams is maintained at [12].

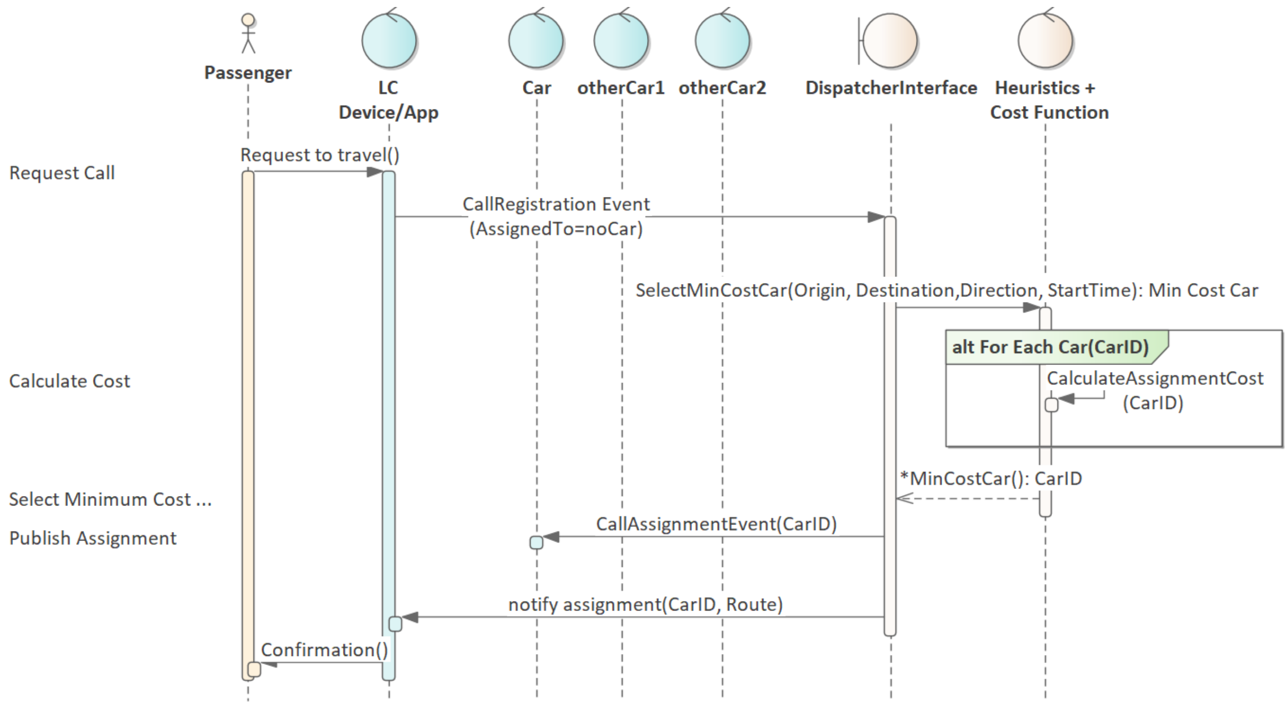

Figure 1 Analysis Use Case Sequence Diagram - Assign Direction Call

3 GDI DESIGN

The outputs of the design phase of the SDLC are:

- Sequence Diagrams
- Class library definitions

These will be the necessary inputs for the subsequent software development phase – in this case development of the prototype.

3.1 Design Requirements

During the elaboration of the sequence diagrams some further design requirements are identified.

3.1.1 Standard Elevator Information Schema (SEIS)

The system use cases are described in terms of messages representing *events* that occur within a lift system. These are changes in the information which describes the state of the lift system and are key to ensuring the interoperability of all systems which communicate via the GDI. It is therefore of critical importance that the communicated information content and inter-relationships are specified in a formal and standardised manner. Such a formal specification is provided by a schema, and the necessary schema already exists - the Standard Elevator Information Schema (SEIS) [13][1].

[1]Where this paper makes references to the data types of the SEIS schema, these are indicated by text in CamelCase, which (for the digital format of this document) includes a hyperlink to the definition on the website where the schema is published [13]

3.1.2 Publish and Subscribe Architecture

It is clear from the analysis sequence diagrams that the assignment resulting from a passenger's request to travel must be communicated not only to the passenger via the source of the request (call device/application) but also, most importantly, to the assigned car (and possibly to all other cars as well). Until the assignment is made, the cars are unaware that a call has been registered. So a mechanism is required that will notify the car(s) without them having to continually poll the dispatcher service "just in case". This mechanism is provided by the Publish-And-Subscribe [14] messaging pattern. With this pattern, any number of active elements (cars, call devices, etc.) may request the GDI to publish a list of observable information sources against which they may submit a "subscribe" request. The GDI will subsequently send a message to all subscribers each time an event occurs associated with the information being observed (described by the Observer software design pattern [15]).

3.1.3 Dispatcher Interface as a "Notice-Board"

It has been shown that the system use case sequence diagrams comprise messages being passed to and from the GDI describing information events (conforming to SEIS) and since these events are updates, it is implied that the GDI must maintain a record of the current state (an information model), which is then to be updated. The GDI ensures that the information model is always kept up to date and acts like a central notice-board where the elements of the lift system simply post their current status, under specific subject headings (defined by SEIS). Coupled with the publish-and-subscribe architecture, it becomes like a social-media notice-board where subjects of interest can be "followed" (i.e. subscribed to). This is a very important property of the GDI since none of the lift system elements is assuming to understand or maintain expectations of the operation (or even the existence) of any other element which may receive its messages. In software engineering this characteristic is referred to as 'separation of concerns' [16].

The resulting interface is compatible with any dispatcher algorithm technique from dynamic sectoring to neural networks based on cost functions, and therefore the inevitable debate is avoided about which parameters must be passed in any call to the interface.

This mode of interaction allows an enormous amount of flexibility in the configuration and component architecture of lift systems which may use the GDI. Figure 2 illustrates some of the many possible configuration options.

3.2 Component Architecture Flexibility

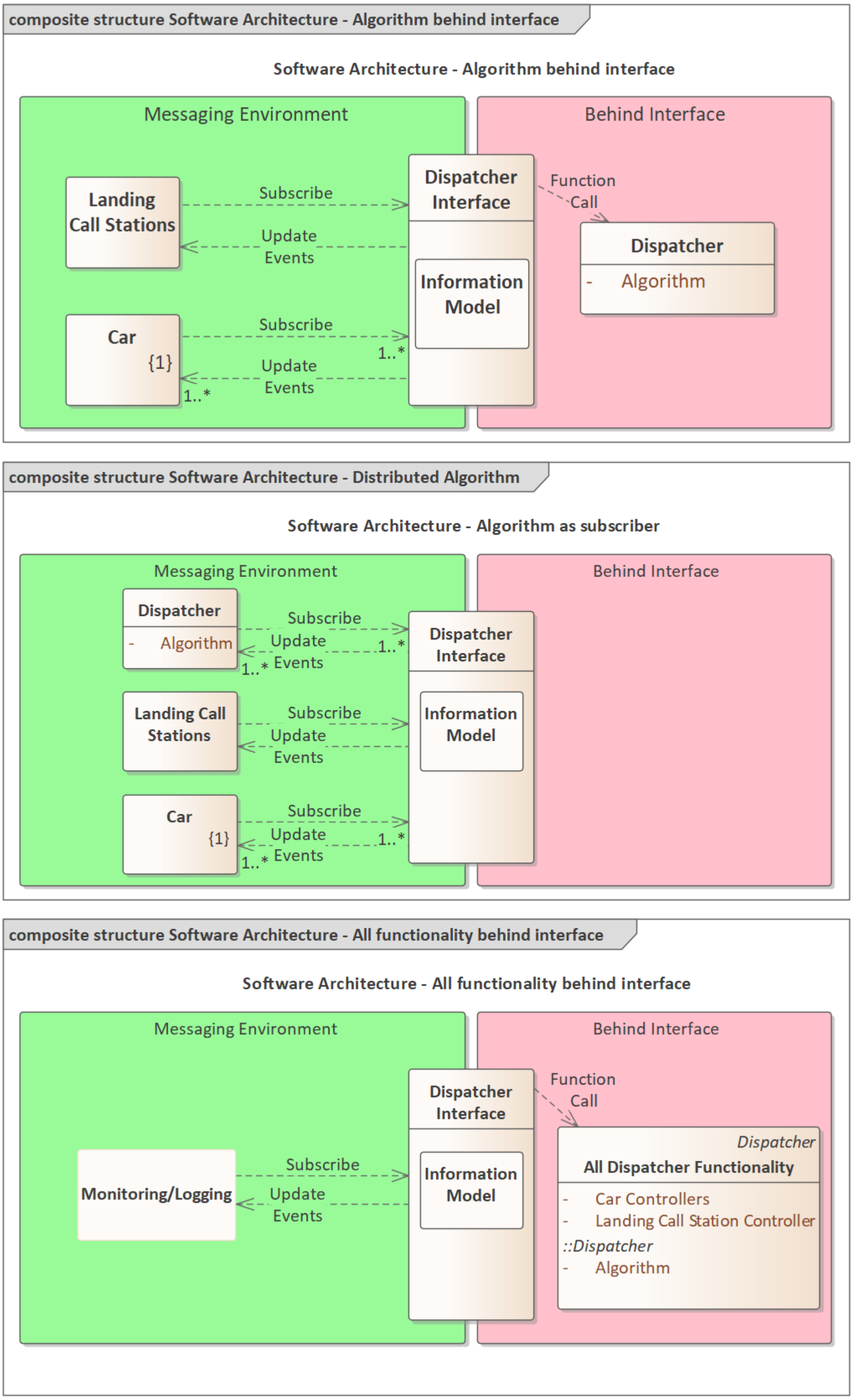

Figure 2 Some GDI architecture options

3.2.1 Configuration option - Algorithm Behind Interface

The use case sequence diagram (Figure 1) shows the cars and landing call devices sending messages to the dispatcher interface with the dispatcher algorithm located “behind” the interface, implying a simple function call from the algorithm to update the information maintained by the dispatcher interface with the assignment result.

3.2.2 Configuration option - Algorithm as Subscriber

In some configurations it may be more appropriate for the algorithm to be implemented simply as another subscriber to the interface (a.k.a. Notice-Board) leaving nothing “behind” the interface.

3.2.3 Configuration option - All Functionality Behind Interface

On the other hand, in some circumstances it may be preferred to have all elements of the lift system control software implemented as a single software component that sits “behind” the interface. In this case the interface would operate simply as a reporting mechanism via which data logging and status monitoring equipment could be connected.

3.3 RESTful Interface

It has already been noted that messages to and from the GDI represent information events that are defined in terms of SEIS. Each message is either placing new information into the information model or reading the current state from the information model. Updates of the information model might simply change the value of an existing element in a list of the information model, e.g. Car4 Direction is now UP (the action of this message is called “PUT”). Alternatively, the event message may create a new element in a list, e.g. a landing call has been registered (the action of this message is called “POST”). In this case a unique identifier is attached to the element so that it can be referenced in future, for example when information is read from the information model (the action of this message is called “GET”). We can conclude therefore that messages do not make calls to the specific functions of the dispatcher, nor any other aspect of operation of passenger lifts. Instead, the same set of standard generic functions (called “methods”)

- POST
- PUT
- GET

can be requested from each observable node of the information model.

These functions might be implemented as a ‘RESTful’ [17] interface which may be implemented in a variety of available programming technologies and languages. The elements of the information model are “resources” in REST terminology. Furthermore, we see that resources which have a multiplicity greater than 1 (i.e. lists) must support queries using the properties and referenced links of the node.

A valuable characteristic of REST is its independence of any network topology (e.g. proxies, gateways, firewalls, etc.), so it is scalable. If required, a single instance of the GDI might therefore support a number of groups of lifts, located in the same building or campus or might even be made available via the Internet as a cloud service. Conversely, one large group of lifts serving many floors will have a heavy computational burden and so might require multiple instances of the dispatcher to be accessed transparently through what appears to be the same GDI.

The GDI prototype complies with all 6 REST constraints – see [17]. Additionally, access permissions to each published node (resource) of the SEIS information model must be considered:

3.3.1 Access Rights

The GDI should implement an overall security policy to restrict access (including subscription) to authorised clients only. Access rights will be established during execution of the Registration use case, but this is not discussed further in the current paper.

3.3.2 Create/Update access restricted to "owned" resources

The ability of a client to create and update resources via the GDI is limited to those resources that are "owned" by the client. Thus a car may update any attributes of its own CarDynamicData or CarStaticData but not those of another car.

Landing call devices may create (POST) a new LandingCall in the list but updating (PUSH) the resulting LandingCall is owned by the dispatcher.

It is a matter of internal design of the dispatcher whether LandingCalls are deleted or retained when their Status becomes Cancelled and should be considered as part of the greater discussion of data logging and retention [2].

4 PROTOTYPE DEMONSTRATOR

The purpose of the prototype is to demonstrate and validate the ability of the GDI design to support the functionality that is particular to the task of lift system dispatching. To achieve this objective, it is necessary to build a complete and realistic environment in which the dispatcher interface can operate. Such an environment needs to have access either to several operational lift installations or to a variety of configurations of simulated groups. The different configurations must allow the prototype to be driven by both direction and destination passenger call stations and to demonstrate different numbers of cars and patterns of passenger demand and floors served. The environment selected for the prototype is illustrated in Figure 3. Implementation and test of the prototype are discussed in greater detail in [7].

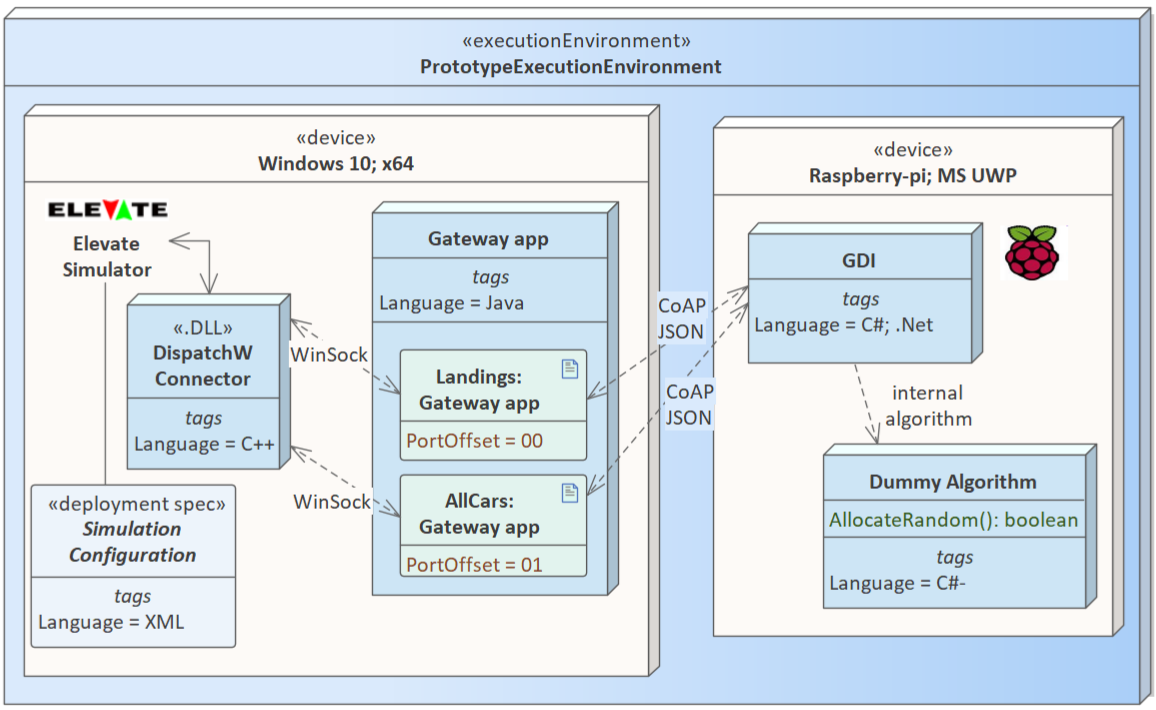

Figure 3 Prototype Implementation

More general technical considerations, such as network performance, security, robustness, etc., are addressed only in as much as it is necessary to achieve a realistic and operational prototype.

In an attempt to demonstrate that the prototype design is not dependent on specific technologies, the selection of network protocols, software frameworks, programming languages, computer hardware and operating system environments has been chosen to be as diverse and heterogeneous as possible and is summarised in the following sub-sections.

4.1 Lift System Simulator

For this prototype, an accurate lift system simulation [9] of lift cars, passengers and call stations has provided a realistic, flexible and permanently accessible solution. Of great importance to the prototype, the dispatcher algorithm, which controls the assignment of landing calls, may be configured as being provided via a system that is external to the simulator. The simulator runs on the Microsoft Windows platform.

4.2 Simulator Connector .DLL

In this case the user-programmable “algorithm” is replaced by connection software (“DispatchW Connector” component in Figure 3 - a Microsoft Windows .DLL). Developed in C++, this doesn’t itself contain the algorithm but instead simply splits the information from the simulator, according to its subject matter (cars or landings calls), into separate streams of data events to produce a more realistic environment (using Microsoft sockets API – WinSock [18]).

4.3 Landing Call-station and Car Gateway Application

In a further attempt at realism, a Gateway software application has been developed to undertake a variety of transformations of the data events received from the simulator and similarly for information being returned in the opposite direction. In order to demonstrate the “global” applicability of the GDI we must consider that any part of the lift equipment interacting with it may not be able to produce the necessary information at the appropriate time or in a suitable format. It may be that some manufacturers would integrate such a gateway with their equipment, thereby maintaining the confidentiality of their own intellectual property. Others may prefer to delegate the development of gateway software to a third party. A similarly flexible approach is specified for the connection of lift systems for data monitoring by the National Standards Committee of the People’s Republic of China [19].

The gateway is written as a Java application, allowing it to run in a very wide variety of operating environments. It communicates with the GDI using the Eclipse Californium CoAP library [20].

4.4 Global Dispatcher Interface Executable

The prototype GDI itself is written in C# and executes on a separate computing device – a Raspberry Pi running the Windows IoT core on the Universal Windows Platform (UWP).

The GDI software is based on a Windows .Net library implementation [21] of CoAP [22] – Constrained Application Protocol – which is specifically designed to minimise processing and communication demands and which:

- supports a RESTful interface and
- enables discovery of resources through the "/.well-known/” URI
- supports subscription to observable resources
- supports a number of message payload formats including JSON, XML and plain-text, which may be used concurrently and interchangeably in a single implementation.

Whilst there are several available alternatives to CoAP, it was chosen because it offers the above capabilities and because the computing power and network bandwidth available to such an application, probably running in the lift motor room, are likely to be 'constrained'. However, an eventual commercial product may well employ a different open standard protocol.

4.5 Global Dispatcher Prototype Sequence Diagram

Now that the components of the prototype have been identified, the design process continues by developing the sequence diagrams illustrating the CoAP message interactions between actual elements of software. Each sequence diagram is a refinement of the corresponding analysis use case sequence diagram. For the purposes of this paper, a single example of a design sequence diagram is presented in Figure 4. For the prototype, the interacting software elements are implemented as independent components, but this is not a requirement, and an integrated single executable may be preferable for eventual commercial product implementation.

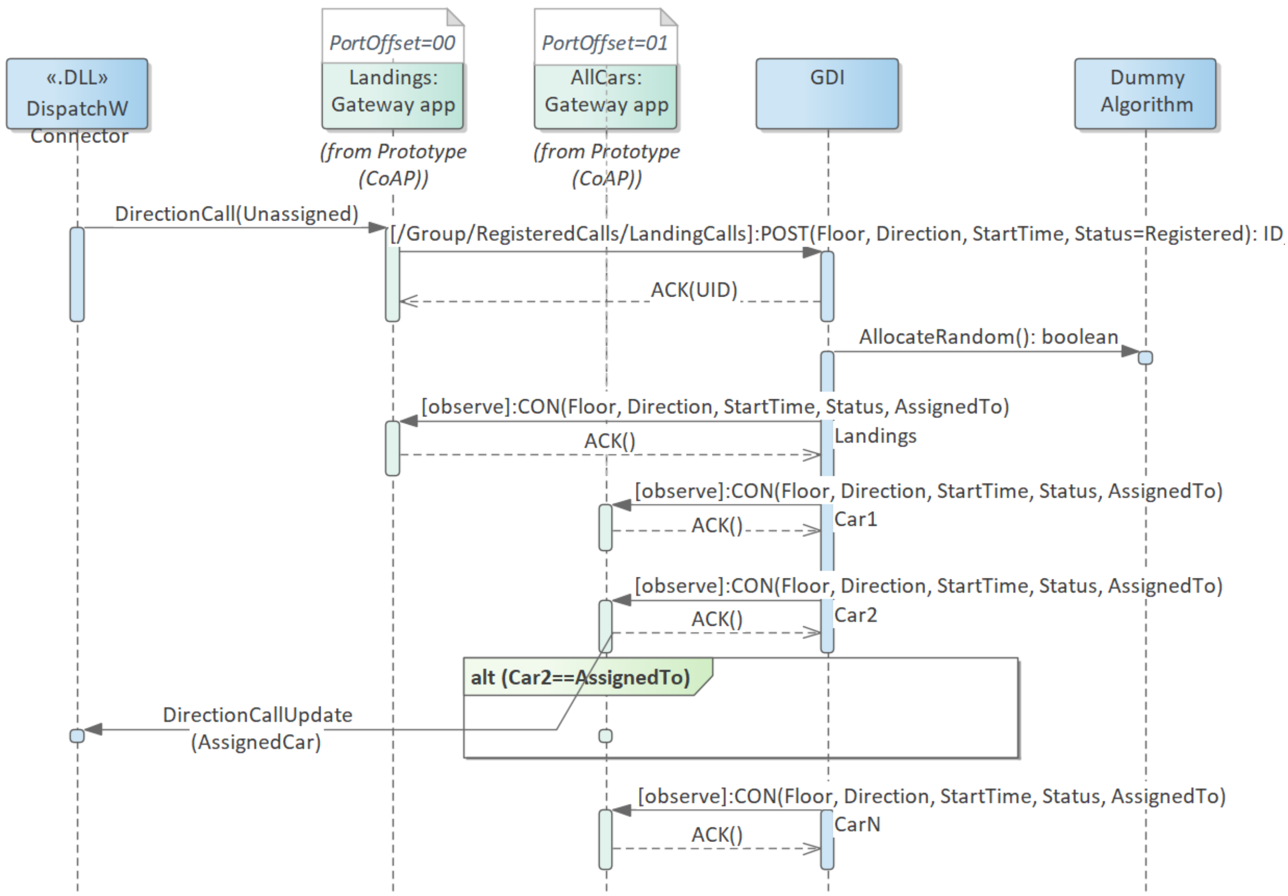

Figure 4 Prototype - Direction Call Registration and Assignment

5 CONCLUSIONS

An overview of the design of a Global Dispatcher Interface has been presented using standard software design methods. Starting with a set of analysis use cases and associated catalogue of requirements, sequence diagrams illustrating the interactions between software components have been developed to document the design of the GDI. A prototype demonstration environment has been built, implementing the GDI design, interoperating via custom gateway software with a realistic software simulation of passengers and lifts in order to validate the design.

The material presented in this paper is part of an ongoing research and development project and has yet to be implemented commercially. The author welcomes comments and questions regarding possible improvements, errors and omissions. The next iteration of the prototype will explore and validate the potential offered by a distributed dispatcher interface.

5.1 End Note - Security

The introduction to this paper noted that the prototype, which is its subject, does not address general requirements of the GDI that are not specific to the domain of lift systems dispatching. However, it is important to stress in these concluding remarks that security must be placed at the forefront of considerations when developing a commercial product embodying the GDI. Even where the GDI is not connected directly to external networks, it is nonetheless capable of acting as an unintended route for malicious agents to gain access to the lifts or other external systems. Therefore, a full risk assessment must be carried out on a regular basis (extending throughout the product lifetime), and any exposed risks mitigated by regular updates. Refer to *CIBSE Guide D. 2020 Transportation Systems in Buildings* [2] for a more detailed discussion.

REFERENCES

[1] Barney, G.C. and Al-Sharif, L. (2016) Elevator Traffic Handbook, Second edition, Chap.12, Routledge, Abingdon UK, 2016, ISBN 978-1-138-85232-7.

[2] CIBSE-Ch14. (2020). *CIBSE Guide D. 2020 Transportation Systems in Buildings*. Chap 14, The Chartered Institution of Building Services Engineers.

[3] Beebe, J (2018). "*Towards A Global Traffic Control (Dispatcher) Algorithm - Requirements Analysis*", Transportation Systems In Buildings, Vol 2, No 1 (2018), University of Northampton, Available from: http://journals.northampton.ac.uk/index.php/tsib/article/view/147 . (accessed 05-Jun-2022)

[4] SDLC(2021) see "*Software development process"*, Wikipedia, Available from: https://en.wikipedia.org/wiki/Software_development_process. (accessed 11-Jul-2022)

[5] Beebe, J (2021), "*Analysis products*"; https://dispatcher.std4lift.info/ (accessed 11-Jul-2022)

[6] Sparx (2021), Sparx Systems Enterprise Architect. Available from: https://www.sparxsystems.com/ (accessed 11-Jul-2022)

[7] Beebe, J (2022). "*Towards A Global Traffic Control (Dispatcher) Algorithm - Interface prototype design*", Transportation Systems In Buildings, Vol 4, No 1 (2022), University of Northampton, Available from: http://journals.northampton.ac.uk/index.php/tsib/article/view/158 (accessed 05-Jun-2022)

[8] Software Prototyping (2021), see Software prototyping, Wikipedia, Available from: https://en.wikipedia.org/wiki/Software_prototyping. (accessed 11-Jul-2022)

[9] Peters Research (2021). Elevate™ traffic analysis and simulation software. Available from: https://www.peters-research.com/index.php/elevate/about-elevate. (accessed 11-Jul-2022)

[10] Alhir, Sinan Si.(1998), "UML in a nutshell"; pp85-94 "*Sequence Diagrams*", O'Reilly & Associates, Inc., Sebastopol CA, USA, 1998, ISBN 1-56592-488-7.

[11] Bitner, K and Spence, I.(2008), "Use Case Modelling", pp196, "*What is a Scenario*", Addison-Wesley, London, 2008, ISBN 02011709139.

[12] Beebe, J (2021), "Design products"; https://dispatcher.std4lift.info/GlobalDispatcher-PrototypeDesign.pdf (accessed 11-Jul-2022)

[13] Beebe, J. (2021)"Standard Elevator Information Schema", https://www.std4lift.info/ .. (accessed 11-Jul-2022)

[14] Publish-Subscribe (2021), *Publish–subscribe pattern*, Wikipedia, Available from:: https://en.wikipedia.org/wiki/Publish%E2%80%93subscribe_pattern (accessed 11-Jul-2022)

[15] Gamma, et al (1995) Erich Gamma; Richard Helm; Ralph Johnson; John Vlissides (1994). *Design Patterns: Elements of Reusable Object-Oriented Software*. Addison Wesley. pp. 293ff. ISBN 0-201-63361-2.

[16] SeparationOfConcerns (2021). *Separation of concerns*. Wikipedia, Available from: https://en.wikipedia.org/wiki/Separation_of_concerns (accessed 11-Jul-2022)

[17] REST (2021), *Representational State Transfer [Internet]*, Wikipedia, Available from: https://en.wikipedia.org/wiki/Representational_state_transfer (accessed 11-Jul-2022)

[18] WinSock (2021), Microsoft, *Winsock Network Protocol Support in Windows*. Available from : https://docs.microsoft.com/en-us/windows/win32/winsock/network-protocol-support-in-windows (accessed 11-Jul-2022)

[19] PRC (2021) National Standards Committee of People's Republic of China. GB/T 24476-2017 - *Specification for internet of things for lifts, escalators and moving walks*. 2018. Available from: https://www.chinesestandard.net/PDF/English.aspx/GBT24476-2017 (accessed 11-Jul-2022)

[20] Californium (2021), Eclipse Foundation, "*Eclipse Californium*". Available from: https://www.eclipse.org/californium/ (accessed 11-Jul-2022)

[21] Waher, P. (2018), *Mastering Internet of Things*, Chap 10 *The Controller*, Packt Publishing Ltd. (www.packtpub.com),ISBN 978-1-78839-748-3.

[22] CoAP (2014), Internet Engineering Task Force (IETF), "*The Constrained Application Protocol (CoAP)*", RFC 7252. Available from: https://tools.ietf.org/html/rfc7252.(accessed 11-Jul-2022)

[23] JSON (2022), *JavaScript Object Notation*, Wikipedia, Available from: https://en.wikipedia.org/wiki/JSON (accessed 11-Jul-2022)

[24] URI (2022), *Universal Resource Identifier*, Wikipedia, Available from: https://en.wikipedia.org/wiki/Uniform_Resource_Identifier (accessed 11-Jul-2022)

BIOGRAPHICAL DETAILS

Jonathan Beebe has more than 40 years' experience of bringing the latest software design and data modelling technologies into the domain of lift system control and monitoring. Following his PhD thesis entitled "Lift Management" (completed at a time when there were virtually no computer-controlled lifts anywhere in the world) he was employed to design and implement software for dispatcher algorithms and single car controllers coupled with a remote performance monitoring system.

Throughout his career Jonathan has maintained an active interest in research, resulting in the publication of The Standard Elevator Information Schema (SEIS) in 2003. SEIS is published under the Creative Commons licence with free and open access to anyone interested.

Jonathan's current research project is developing a Global Dispatcher Interface (GDI), based entirely on the SEIS. GDI looks forward to the era of smart buildings and cities in which vertical transportation systems will play a fundamental role.

Lift Industry and BIM: A Long Overdue Adopted and Typically Overlooked Project Enabler

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Keywords: BIM, Digitalisation, Digital Construction

Abstract. BIM (Building Information Modelling) shall not be a new term for any individual or enterprise working in the construction industry. However, the Vertical Transportation industry still finds the use of BIM as rather "new" despite being mandatory in certain countries for all public projects since a few years. BIM has proven itself as an enabler for different actors inside the construction industry: Investors, Builders, Lead Designers and Facilities Managers can benefit from a faster and more accurate deliverables creation. The digital models of the lifts and escalators are fully integrated and coordinated with the architectural and structural models since the beginning of the project which leads to a quicker design approval and therefore a faster release to manufacture. All this combined with the reduction of the mistakes on site leads to a higher customer satisfaction rate.

The use of BIM models during the operational phase is becoming more and more important with the rise and the need to provide Digital Building Twins. BIM Models are the foundation of the Digital Building Twins and therefore these shall be accurate and contain the relevant information for the Facilities Managers. Accurate and up to date models (these need to reflect the current condition of the installed assets) can also serve as a solid foundation to plan modernisation jobs. The rise of drone surveying as well as 3D laser scans could be of great use to modernisation teams looking to install new products into existing buildings.

1 INTRODUCTION

Over the past decade, the evolution of technology has reached an incredible pace. This pace has made it hard for individuals as well as businesses to keep up with the latest technologies.

The construction industry is not known for its efficiency and innovation but some of these technologies have made their way into the construction industry. BIM could have been the first attempt the construction industry has had to digitalise and streamline its processes as well as increase the collaboration amongst project teams.

This paper will take a brief look at how BIM can help the Vertical Transportation industry to be a more integrated discipline within construction projects and how the use of BIM processes can help Vertical Transportation professionals to deliver projects more accurately, efficiently and with a higher quality.

It must be noted that the delivery of construction projects using BIM for Vertical Transportation follows a different approach to how architects or structural engineers develop and deliver their projects. Whilst most of the disciplines produce their designs on a floor-by-floor basis, Lifts and Escalators must cross inevitably more than one floor at a time.

2 BIM (BUILDING INFORMATION MODELLING)

2.1 Definition

BIM is defined in ISO19650-1 as the "use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions" [1].

2.2 Misconceptions

BIM has been around for a relatively long time in the construction industry, but it is understood as a new or unknown term for most Vertical Transportation professionals. When confronted for the first time with the question: can your company comply with the project BIM requirements? Vertical Transportation companies start to look for answers (e.g. in their engineering department) that give them enough confidence to reply positively to their customers. Some of these answers may take these companies into the wrong direction. The following paragraphs will describe what BIM is NOT:

- BIM is NOT just a 3D model: while it is true that 3D models are produced as part of the BIM deliverables, there is much more to BIM than just a 3D model. Long gone are the days where disciplines were developing their entire project using traditional 2D based approaches and delivering just a 3D model at the end of the project. This practice was not just inefficient but also not compliant with customer and standards requirements.

- BIM is NOT just the use of a new piece of software: it was also believed that by purchasing an expensive piece of software and enrolling a few engineers in a one-week course where they will be taught how to use this new piece of software, their company will be BIM compliant. Although it is common that new software is used to produce certain deliverables, it cannot be forgotten that BIM is not just an internal engineering task but a teamwork amongst all actors delivering a construction project.

- BIM does NOT take more time, effort and cost than traditional methods: delivering a BIM project does not take more time, effort nor is it more expensive than doing it using traditional methods. On the contrary, BIM allows Vertical Transportation companies to deliver projects quicker and more accurately. It must be said that the BIM journey is not easy, and it does not happen overnight but once the company has adopted BIM as their standard way to deliver construction projects, all the benefits will be materialised.

2.3 The benefits of BIM

Vertical Transportation equipment are a key part of the building, and several actors can benefit of the use of BIM. The main actors and Global Benefits (applicable to the whole construction project) are listed below:

Investor:

- Reduce the number of errors during installation and operation.
- Better understanding of building functionality and limitations
- Easier asset tracking and cost reduction.
- Earlier completion

Builder:

- Faster design approval
- Reduction of mistakes on site
- Greater transparency
- Greater insights into building operation and potential modernisations

Consultant / Lead Designer:

- Easier coordination for global entities

- Improved communication and collaboration
- Greater transparency of all contributions
- Earlier error identification

Facilities Manager:

- Monitor equipment status
- Schedule for maintenance visits
- Greater cost predictability
- Greater insights into building operation and potential modernizations

Global Benefits:

- Faster and more accurate deliverables creation
- Faster design approval due to the high integration of Vertical Transportation's equipment in the building
- Faster release to manufacture due to the earlier design approval (better understanding on how Vertical Transportation's equipment interacts with all the other disciplines)
- Better site coordination
- Reduction of mistakes on site
- Consistent data used for different purposes
- Develop and motivate employees by using innovative technologies and processes
- Higher customer satisfaction rate

3 THE USE OF BIM THROUGHOUT THE PROJECT LIFE CYCLE

3.1 Design Phase - Front Loading

An early project engagement is not only beneficial for the Vertical Transportation manufacturers but for the entire project team.

BIM workflows bring the effort closer to the beginning of the project and incentivise the project team to collaborate more openly during the early stages of the project. With this collaborative process in place, errors can be identified when the cost for design changes is minimal, as the cost for design changes increases exponentially as the project progresses. By shifting the collaboration effort towards the beginning of the project, teams can find the most optimal solution for the building needs in a more effective way. At this stage the building constraints are not totally defined, and project parties are able to bring proposals to the table that will improve the design and performance of the building at a stage where changes are still economically and technically feasible.

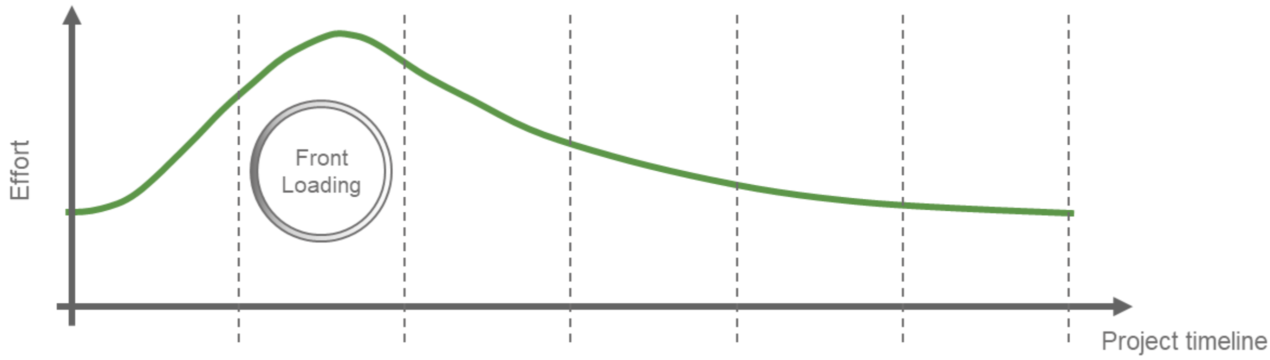


Figure 1. Frontloading. [2]

This collaboration is particularly important for complex systems such lifts and escalators. This equipment needs several interfaces to the building and other systems to be installed and to perform optimally. These interfaces can, amongst others, be mechanical, electrical and structural. The figure below represents the headroom of a group of two lifts, whose machine room sits below at the back of the lift shaft and a pulley room is built at the headroom of the lift shafts.

Following a full integrated BIM process, the lifts are sitting in the correct geo-location inside the digital building mock-up. In this particular case, the lifts use as a reference (link) the structural and architectural models and communicate the lift needs to other parties including all necessary interfaces for the correct installation of the equipment.

Particularly, in this figure the structural pockets needed for the installation of the beams, anchor channels and lifting eyes are clearly visible and communicated to other parties through the model. Structural engineers will need to simply link the lift models into their models and confirm the feasibility of the proposal. In case of doubt, a BIM coordination meeting can be organised, and concerns can be raised from both sides to find the most suitable solution for each application.

The coordination during the design phase has been made easier with the use of tools such as BIM Track which allow participants to raise concerns, issues, etc. to other parties and clashes or design misalignments can be resolved in a collaborative way using the models. This practice makes the iterative process more agile, and conflicts are solved in a few minutes instead of weeks of comments back and forth made on 2D drawings. To make the best use possible of such tools, the Vertical Transportation provider shall be fully embedded in the BIM process and ensure that not only engineers but also project and installation managers are upskilled to use and understand not only the tools but also the process.

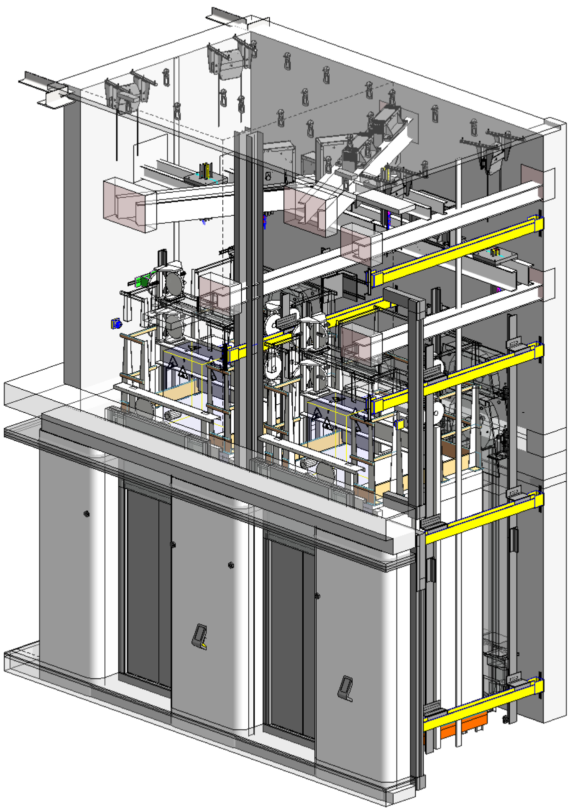


Figure 2. Lift design coordination using BIM models. [3]

3.2 Execution Phase

Once the design has been coordinated amongst all parties, the execution starts. At this stage of the project, BIM can be used in several areas.

The combination of lift models and building models will allow the engineers to produce totally accurate 2D drawings for the installation teams that reflect the current condition of the building as the lift shaft's dimensions and architectural finishes will be obtained directly from the linked structural and architectural models. As the 2D are obtained directly from the 3D BIM models, these will be up to date and if there is any change in the building model and possible conflicts can be spotted by the project team in real time. The collaborative process, once more, ensures that these potential discrepancies are not found on site but in the digital models, where solutions can be discussed and agreed rather than fixing it on site, which can be costly and take much more time and resources.

Once the project gets closer to completion, other building services may need interaction with the lifts or lift spaces such as the Machine Room. The figure below shows how all related services in the Machine Room have been coordinated using BIM models. Air conditioning, lighting, electrical equipment, cable trays and fire equipment amongst others are all coordinated using BIM models. This practice makes the process quicker as all participants can sit around the same virtual model and choose the most appropriate location for each piece of equipment and do all the preparation work accurately and on time so by the time the equipment arrives on site, the installation teams can start their tasks straightaway.

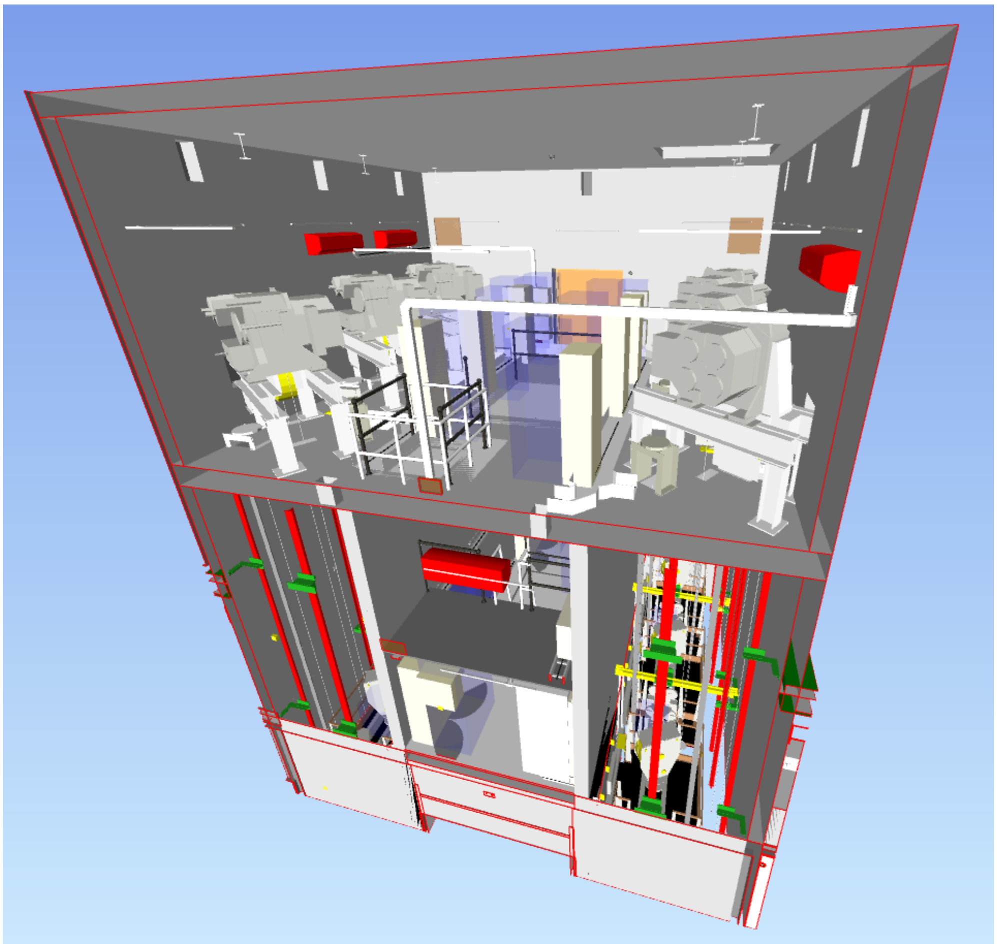


Figure 3. Coordination of lift equipment, building and fire services in the Machine Room. [4]

Another use BIM models can bring to the project is the management of the construction site. BIM models can be linked to tasks to track, for example, the installation status of the entire project or of single lifts. These tasks are governed by a typical project management Gantt chart and provide a visual overview of the status of the installation, commissioning, and lifts in BBU (Builders Beneficial Use). The advantage of this method is that the models and the Gantt chart are linked and as long as the project manager keeps the Gantt chart up to date, with a simple click to refresh the data source, the model will automatically update and display the correct project status.

The figure below shows the footprint of a building with several lifts and the project Gantt chart. The lifts and escalators' names and project duration have been hidden intentionally.

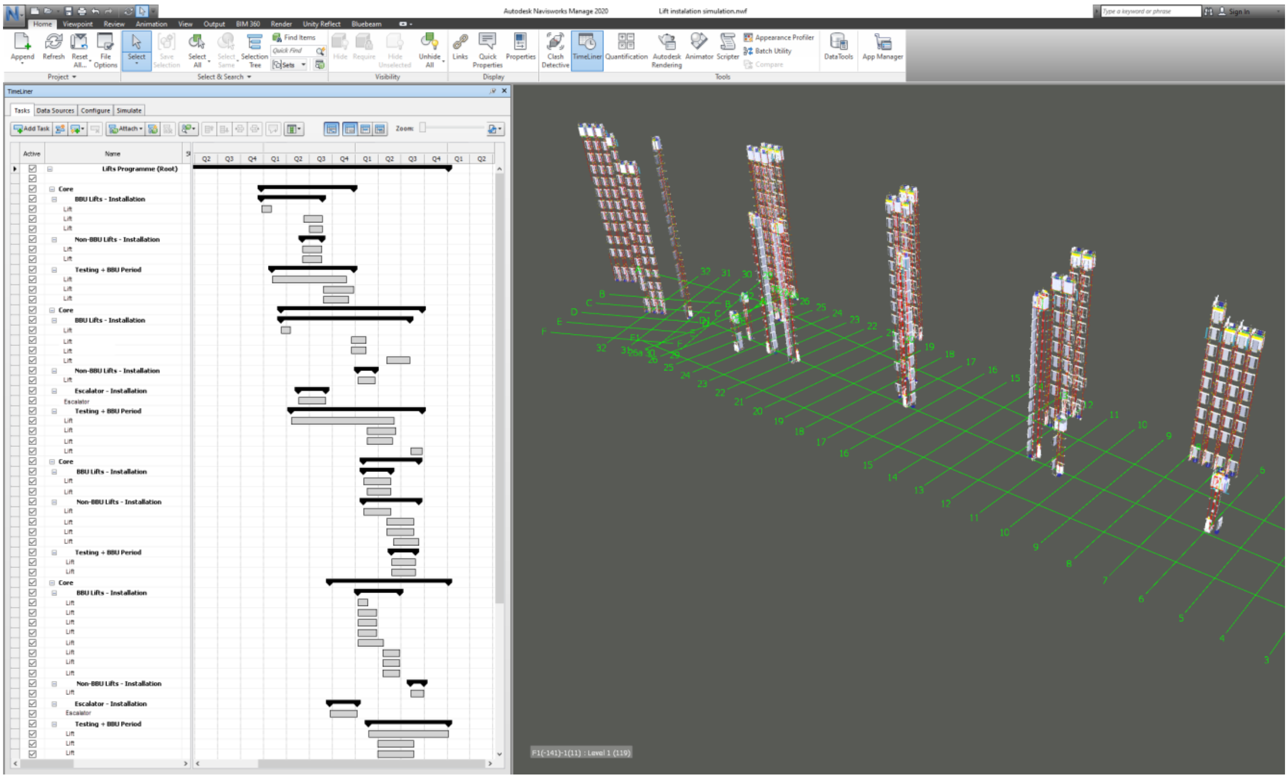


Figure 4. Linking Project Gantt Chart and BIM models for site management. [5]

The figure below shows the project at a certain moment in time and intends to show how a project simulation can be created. Lifts that are being installed at that point in time are represented in green, and solid models indicate lifts that are installed, commissioned and in operation whilst the purple-coloured lifts are in BBU.

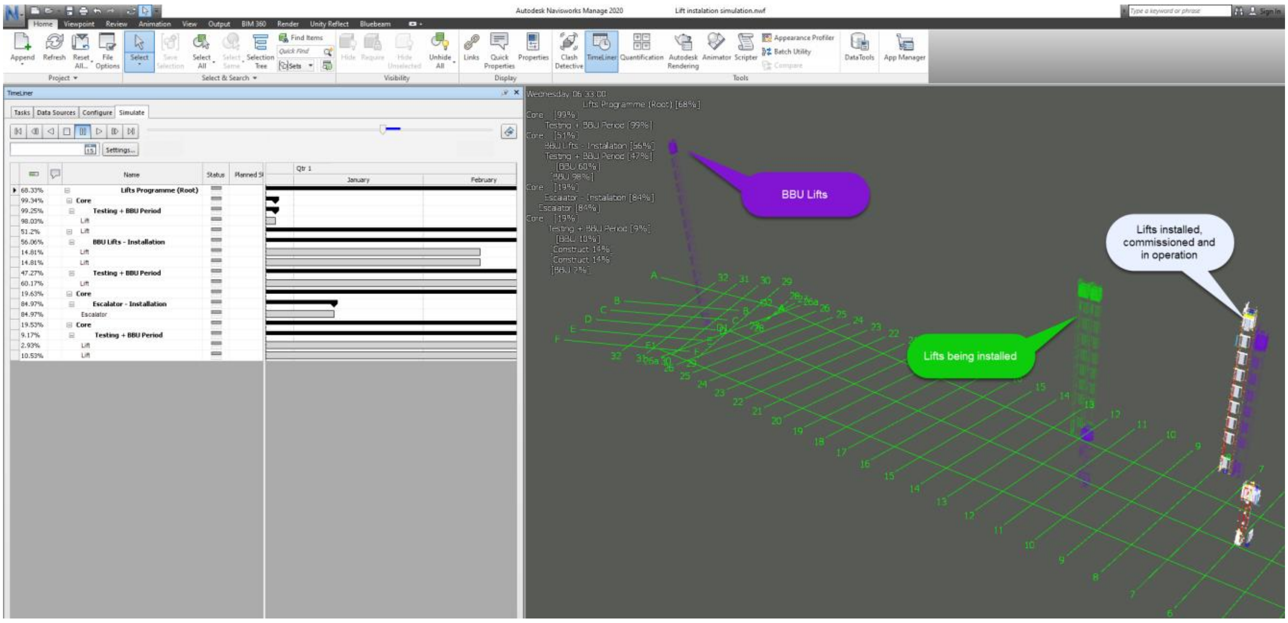


Figure 5. Project progress management using BIM Models. [6]

BIM Models can also be used to produce AR (Augmented Reality) models with out of the box solutions that allow project teams to review designs using mobile devices, in any location, either in the office, factory or even on site to overlay these models over the real lift shaft to validate that the installation has been correctly executed.

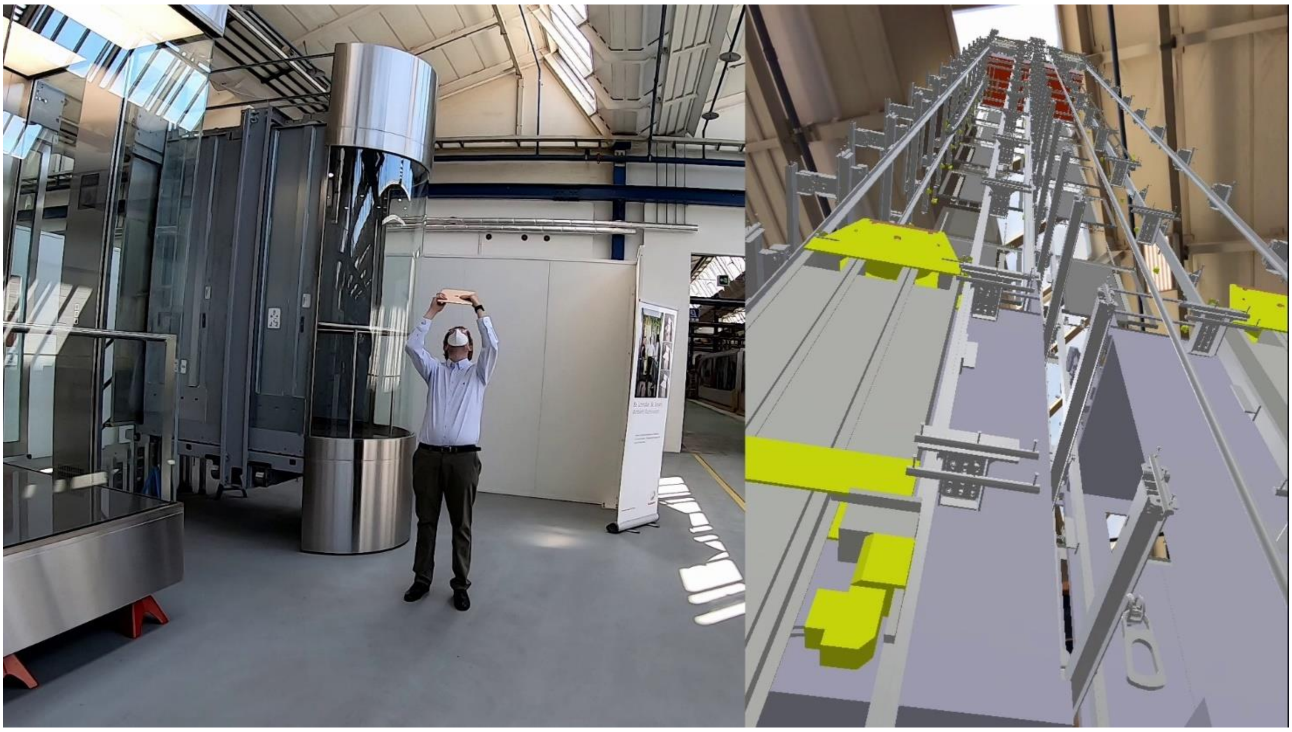


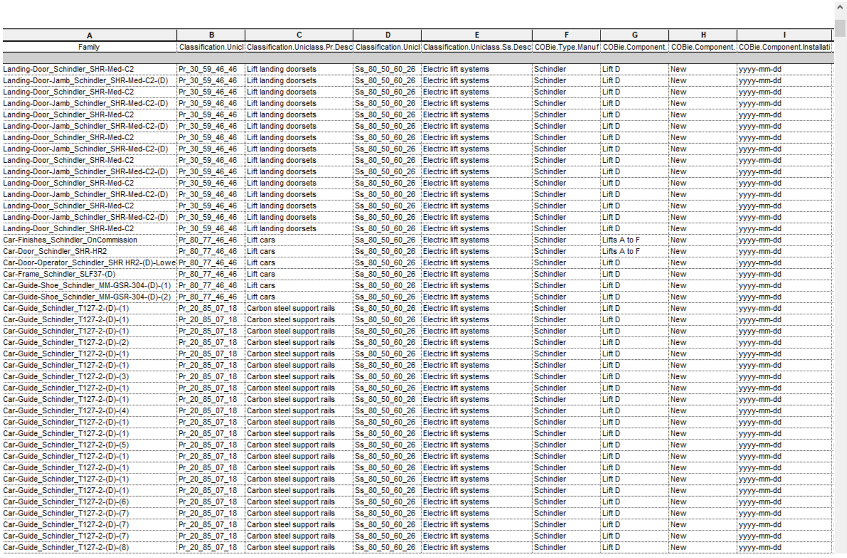
Figure 6. Virtual review of a lift installation using AR (Augmented Reality). [7]

One of the most important, and typically forgotten, piece of information to be produced is the so called, As-Built information. All BIM deliverables, after installation and commissioning, are to be updated to reflect the current site conditions. Once models are updated, all associated deliverables (e.g., 2D drawings, metadata, BOM (Bill Of Materials), etc.) update automatically as the BIM models are the source of all the deliverables.

3.3 Operational Phase

It was mentioned in section 2 of this paper, that one of the myths around BIM was that BIM is just a 3D model. This paper has shown that a BIM model is much more than just 3D geometry. The production of accurate As-Built information is crucial for most customers using BIM at its full potential. These models contain what is generally known as metadata (component and system information). When models are correctly setup and all parties contribute to include the appropriate metadata as requested by the customer, the models can be the base for a model Facilities Management system which allows the operator of the building to have an accurate model that contains the right components with the right information embedded on them.

The figure below shows the embedded information for Facilities Management use. The customer has defined the most important information for all building components (including for lifts and escalators) and the relevant information was embedded in the model. Once all the As-Built information was produced, this model was automatically converted to an Asset Information Model and handed over to the operator of the building.



A	B	C	D	E	F	G	H	I
Family	Classification.Unicl	Classification.Uniclass.Pr.Desc	Classification.Unicl	Classification.Uniclass.Ss.Desc	COBie.Type.Manuf	COBie.Component.	COBie.Component.	COBie.Component.Installati
Landing-Door_Schindler_SHR-Med-C2	Pr_30_59_46_46	Lift landing doorsets	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Landing-Door-Jamb_Schindler_SHR-Med-C2-(D)	Pr_30_59_46_46	Lift landing doorsets	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Landing-Door_Schindler_SHR-Med-C2	Pr_30_59_46_46	Lift landing doorsets	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Landing-Door-Jamb_Schindler_SHR-Med-C2-(D)	Pr_30_59_46_46	Lift landing doorsets	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Landing-Door_Schindler_SHR-Med-C2	Pr_30_59_46_46	Lift landing doorsets	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Landing-Door-Jamb_Schindler_SHR-Med-C2-(D)	Pr_30_59_46_46	Lift landing doorsets	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Landing-Door_Schindler_SHR-Med-C2	Pr_30_59_46_46	Lift landing doorsets	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Landing-Door-Jamb_Schindler_SHR-Med-C2-(D)	Pr_30_59_46_46	Lift landing doorsets	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Landing-Door_Schindler_SHR-Med-C2	Pr_30_59_46_46	Lift landing doorsets	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Landing-Door-Jamb_Schindler_SHR-Med-C2-(D)	Pr_30_59_46_46	Lift landing doorsets	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Landing-Door_Schindler_SHR-Med-C2	Pr_30_59_46_46	Lift landing doorsets	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Landing-Door-Jamb_Schindler_SHR-Med-C2-(D)	Pr_30_59_46_46	Lift landing doorsets	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Landing-Door_Schindler_SHR-Med-C2	Pr_30_59_46_46	Lift landing doorsets	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Landing-Door-Jamb_Schindler_SHR-Med-C2-(D)	Pr_30_59_46_46	Lift landing doorsets	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Landing-Door_Schindler_SHR-Med-C2	Pr_30_59_46_46	Lift landing doorsets	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Finishes_Schindler_OnCommission	Pr_80_77_46_46	Lift cars	Ss_80_50_60_26	Electric lift systems	Schindler	Lifts A to F	New	yyyy-mm-dd
Car-Door_Schindler_SHR-HR2	Pr_80_77_46_46	Lift cars	Ss_80_50_60_26	Electric lift systems	Schindler	Lifts A to F	New	yyyy-mm-dd
Car-Door-Operator_Schindler_SHR HR2-(D)-Lowe	Pr_80_77_46_46	Lift cars	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Frame_Schindler_SLF37-(D)	Pr_80_77_46_46	Lift cars	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide-Shoe_Schindler_MM-GSR-304-(D)-(1)	Pr_80_77_46_46	Lift cars	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide-Shoe_Schindler_MM-GSR-304-(D)-(2)	Pr_80_77_46_46	Lift cars	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(1)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(1)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(1)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(2)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(1)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(1)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(3)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(1)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(1)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(4)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(1)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(1)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(5)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(1)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(1)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(1)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(1)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(6)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(7)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(7)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(7)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd
Car-Guide_Schindler_T127-2-(D)-(8)	Pr_20_85_07_18	Carbon steel support rails	Ss_80_50_60_26	Electric lift systems	Schindler	Lift D	New	yyyy-mm-dd

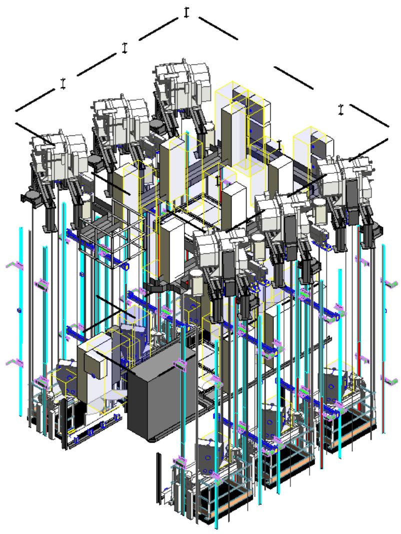


Figure 7. BIM Model with embedded data for Facilities Management use. [8]

3.4 Modernisations

One of the most challenging areas in the Vertical Transportation industry is to modernise existing equipment. Site surveys are a very specialised job that require extensive lift experience and deep knowledge to ensure the dimensions are taken safely and correctly in the limited time available engineers have to perform the site survey.

3D laser scans can help to produce point clouds from which engineers can take very accurate dimensions from the comfort of their office. These point clouds can serve as the basis of the potential new BIM models created for the modernisation of the existing equipment.

The figure below illustrates the result of a laser scan performed from the top of an existing car using a 3D scanner.

Figure 8. Processed point cloud of a lift shaft taken from the top of the car. [9]

Software can process the point cloud and allow the engineers to check the desired dimensions with millimetric accuracy from their office while the lift is back in operation.

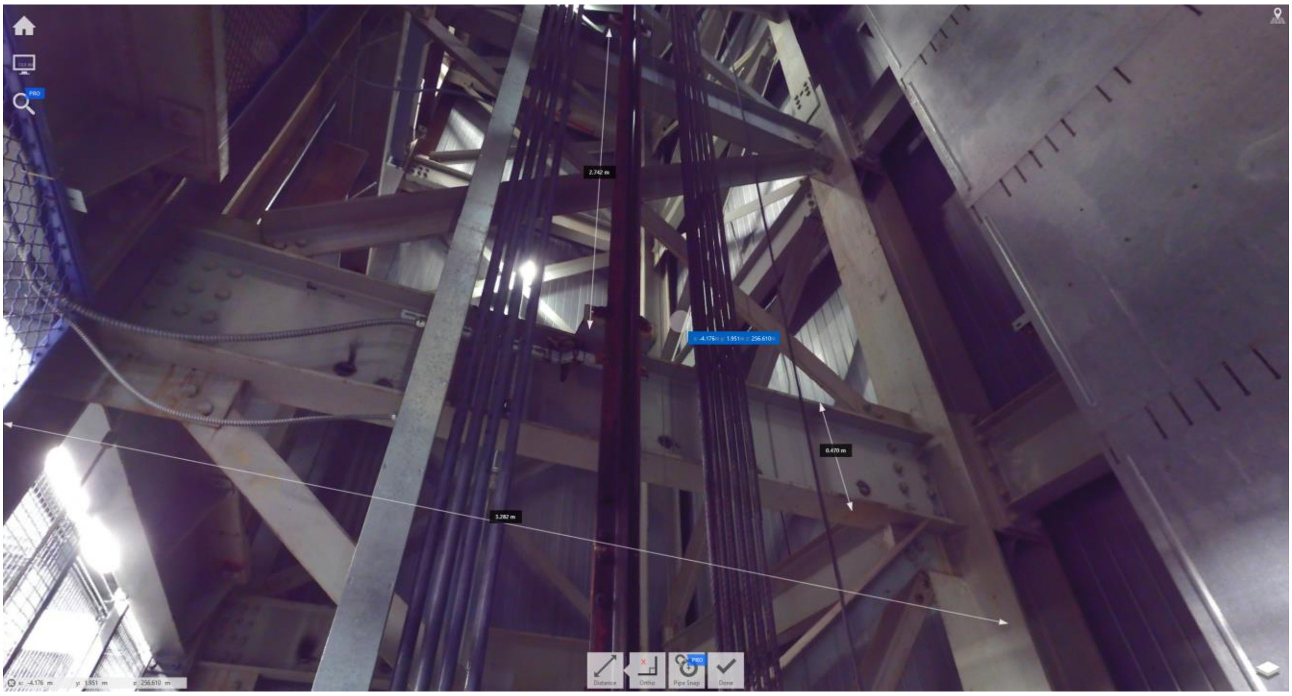


Figure 9 . Processed point cloud of a lift shaft taken from the top of the car. [10]

The use of point clouds is a well-known practice in other areas of the construction industry. The Vertical Transportation industry has not adopted this method as a standard way of carrying out site surveys while other disciplines already have specialised teams that carry out surveys using 3D laser scanners and even drones to map vast extensions such railway tunnels or mines. There is a lot that the Vertical Transportation industry could learn from these practices to ensure surveys are made more accurate and a better and more efficient solution is delivered to customers, reducing the down time of the existing lifts while carrying out surveys.

4 SUMMARY

This paper has shown how state of the art technologies and processes that are already daily business for other disciplines in the construction industry, could help the lift industry to move forward, work more collaboratively and increase efficiency when delivering projects.

5 LITERATURE REFERENCES

[1] ISO 19650-1, "*Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling — Part 1: Concepts and principles.*" Geneva (2018).

[2], [3], [5], [6], [7], [8], [9], [10], Schindler internal documentation.

BIOGRAPHICAL DETAILS

Miguel Castro is an enthusiastic young leader with 10 years of experience in a multinational and multicultural environment, fascinated by technology. He has a broad knowledge of operational processes and application of modern digital technologies to the construction site.

Exploring IoT Applications for Vertical Transportation (VT) to Tackle Challenges in a Modern World

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Keywords: IoT, Lift Maintenance, Covid-19, Air Quality, Net-Zero, Energy Consumption, Lift Monitoring.

Abstract. This paper investigates and proposes applications for emerging, off-the-shelf technologies for vertical transportation (VT) equipment, with a view to tackling some of the changes in social, economic, and environmental requirements of key stakeholders for buildings.

Covid-19 has presented opportunities for IoT technologies to be used within VT systems, to measure air quality and maintain the peace of mind of tenants returning to the office. Sensors have been used to measure a range of in-car, air quality metrics, the analysis of which will be used to recognise how devices can provide stakeholders with accessible, transparent information of the environment in their lifts.

With a drive for energy efficiency, and clients striving to meet their net-zero targets, IoT devices can also be used to monitor energy usage of VT equipment and make strategic decisions to save energy and reduce carbon emissions. This paper also looks to understand if, and how we can measure power used by VT systems with these devices. This, coupled with understanding the changing habits of the average office worker, can be used to think out of the box regarding efficient operation of buildings.

The author's previous research investigated the use of IoT technology to monitor the condition of lifts. Analysis of breakdown data and interviews with key stakeholders were used to demonstrate how this technology could be used for earlier fault diagnosis.

Since the original study, the industry has moved forwards with off-the-shelf and third party IoT systems being trialled by clients and independent suppliers, to support maintenance and repair strategies. Previously, this was only possible with major lift maintenance companies.

1. INTRODUCTION

The expression 'Internet of Things' or 'IoT' is by no means a new concept with the first known 'Smart Device' being created in 1982, where students of Carnegie Mellon University, Pittsburgh, Pennsylvania installed micro switches on a Coca-Cola machine to check the stock levels and temperature of the refrigerated drinks [1]. However, the use of devices to connect VT systems to the internet and collect vast amounts of data is still relatively new, with devices being rolled out by the major lift companies over the past 5-7 years.

In 2019, the author of this paper conducted extensive research into the emergence of this technology. It was found that the introduction of Transmission Control Protocol/Internet Protocol (TCP/IP) v6 [2], along with the advancement of smaller, cheaper, and more powerful chipsets has assisted with the integration of IoT into households and various industries [3]. Heating, ventilation, and air conditioning systems are also using radio frequency identification (RFID) and TCP/IP to connect wirelessly to a network and provide vast amounts of data without human intervention [4].

Kone, Otis, WeMaintain, Thyssen and Schindler have established 'self-developed' systems in the UK and across the world with the aim of producing targeted maintenance regimes to improve reliability, callout response times, transparency, and overall service. The roll out of these systems in the UK has encouraged Clients to push for new, data driven methods of maintenance [5,6,7,8,9].

In 2022 we have seen the emergence of independent, third-party systems being introduced into the market. This equipment is supporting the adoption of IoT technology by the independent lift maintenance providers, with the goal to utilise key data points and provide options for data driven maintenance regimes. It is understood that the key suppliers providing these systems in the UK are Safeline, Thames Valley Controllers, and Kollmorgen with start-up companies in Europe such as Uptime entering the market also.

IoT technology is becoming widely adopted for assisting with maintenance related items, however, the author of this paper has explored different ways in which technology can be used to assist with specific issues relating to:

- Post Covid 19 requirements dictated by tenants' behaviour.
- Ambitious targets for reducing energy usage, carbon emissions and embodied carbon in design.

and,

- Environmental issues seen through prior callout

2. DEVICES

There are various companies that provide off-the-shelf IoT gateway and sensor devices which can be used in a range of applications.

When applying these devices to monitor lift equipment, it is common to encounter the following issues: signal between gateway devices and sensors within lift shafts, signal in motor rooms to allow the gateway devices to connect to the internet and the output of data into user friendly dashboards.

The systems that have been used for the experiments relating to this study are summarised below:

2.1 My Wireless Tag

An American company offering various sensors. This system was used throughout the author's previous study which assisted in understanding what low-cost options were available on the market.

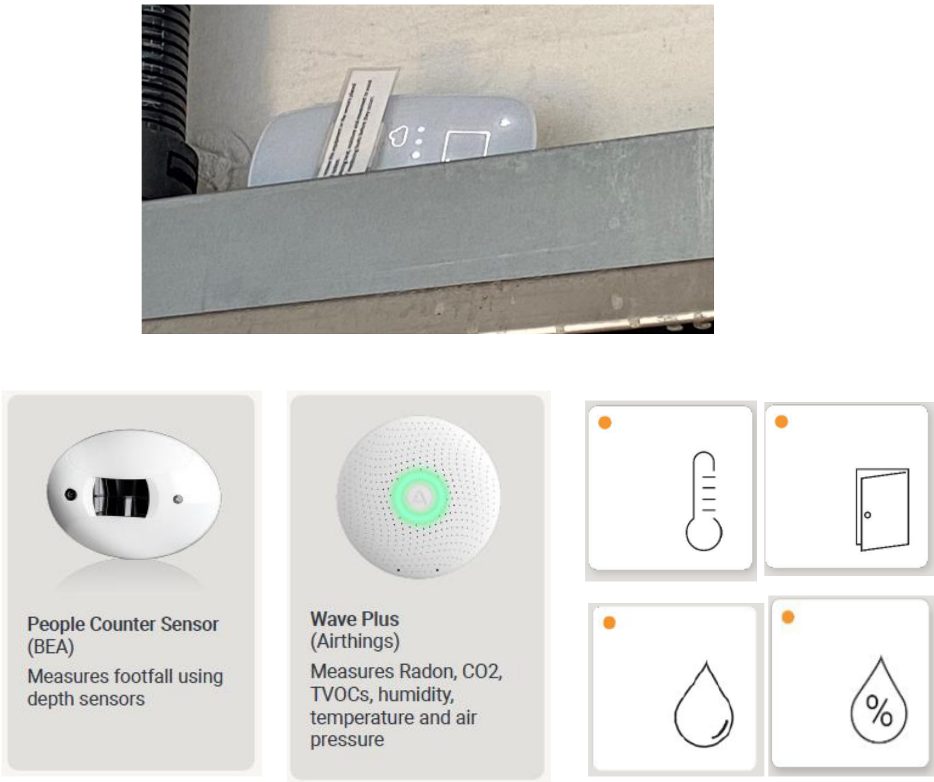
Figures 1a-e My Wireless Tag sensors and gateway device

Whilst this low-cost option proved that off-the-shelf systems are available and can be utilised to assist with earlier diagnosis of callouts, there are various limitations with regards to signal strength, connectivity, dashboard user interface and sensor functionality [10] that have been considered throughout this study.

2.2 InfoGrid

InfoGrid are a venture capitalist funded company who were founded in 2018 and provide various sensors and their own dashboard to present the data in a user-friendly interface.

The devices connect to a sealed gateway unit that has a pre-paid roaming sim card that connects to the strongest data signal available. This removes the issue relating to the complexities of connecting devices to the internet.



Figures 2a-g InfoGrid sensors and gateway device

The available sensors can monitor the following:

- People Counting
- Air Quality
- Temperature
- Door Open/Close
- Moisture/Humidity

These devices are automatically set up to connect direct to the InfoGrid gateway devices which can be located nearby. The devices are simple to set up and provide pre-set graphics to display the data.

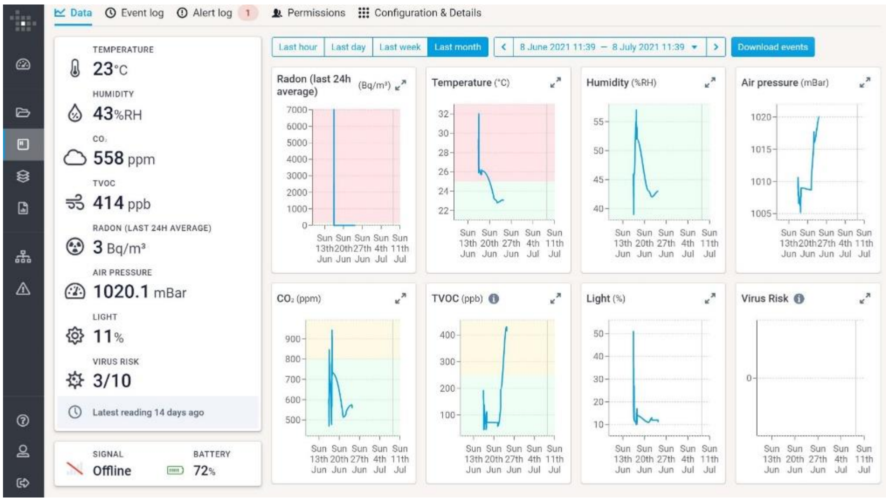


Figure 3 InfoGrid air quality dashboard example

The dashboard provided had some limitations with the functionality, however, the graphics displayed allow the user to customise the view in a way that suits them. A separate gateway device was also required when using the air quality monitoring which increases costs, power, and space requirements.

The people counting device required a 230v power supply and would be located at each landing entrance. Power supplies are not typically provided within close range to lift entrances which made this solution not suitable for lift applications.

There were also constraints with regards to the connectivity of the gateway device when adapting this for a lift shaft. It was estimated that one gateway device would be required at every other floor which would make the system very costly.

The InfoGrid solution was trialled and presented issues that could not be resolved without further significant investment both from the building owner and the author.

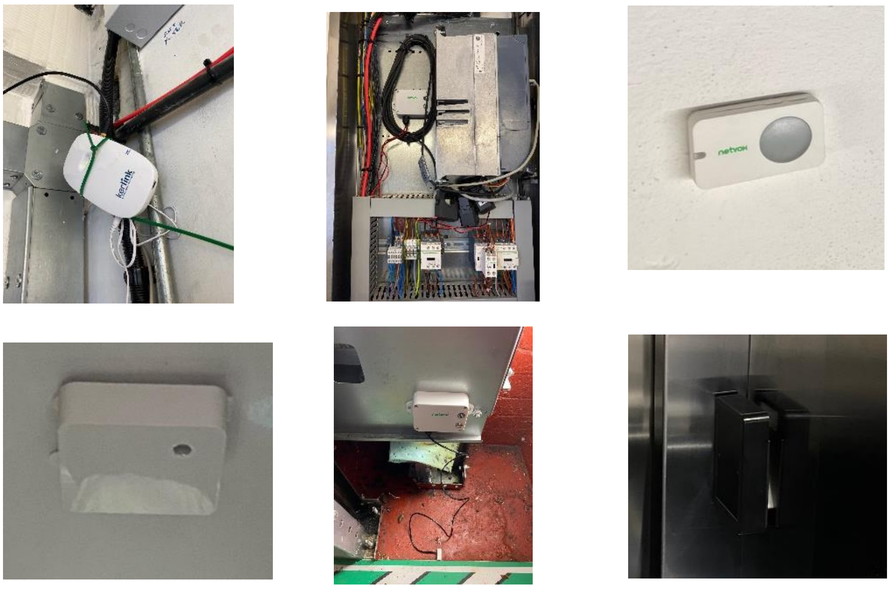
2.3 ALLIoT

Further research into alternative devices that can all be connected via the same gateway led the author to ALLIoT, a company that specialises in providing systems that use low power, long range, wide area network protocols (LoRaWAN technology).

ALLIoT provide a range of different systems and offer consultations to select devices that are most suitable to the application you require. Their services include the gateway devices, sensors, user interfaces (Dashboards) and the data storage all in one package.

Sensors that were available and suitable include:

- Air Quality (Temperature, Humidity & Carbon Dioxide)
- Movement in and out
- Light (measured in LUX)
- 3-Phase energy monitoring
- Water sensor



Figures 4a-f ALLIoT sensors and gateway device

The consultation when designing the system allows for devices to be chosen dependent on the application, it also allowed selection of devices from different manufacturers that all operate on the LoRaWAN network which can connect through the same gateway device.

There were options to use a battery-operated passive infrared (PIR) sensor to measure people movement in and out. This system was suitable as it did not require any infrastructure to use, however, limitations with battery life were a concern.

For the above reasons, the LoRaWAN system was utilised for experiments in this study.

3 OUTCOME

Experiments were undertaken on an 8-Person passenger lift within a commercial building in London.

There are 3 types of dashboards that were available to visualise the data gathered:

- Opensource - Creating dashboard with our own in-house software engineers.
- Pre-Built Public Dashboards - This is recommended for trials due to pricing and functionality.
- Bespoke Platform – Fully tailored to the users' requirements.

The devices were strategically placed around the lift and visualisations of the data were available on the Kheiron dashboard system, a pre-built public dashboard.

If required, the dashboards are interchangeable with all LoRaWAN sensors, so if a dashboard is not the right fit and we swap all data can be transferred.

Figure 5 ALLIoT air quality dashboard example

3.1 Signal

To remove the connectivity issues that had been experienced before, the system purchased included an antenna extension and a field test device which ensured signal was available when placing the sensors in discreet areas of the lift system.

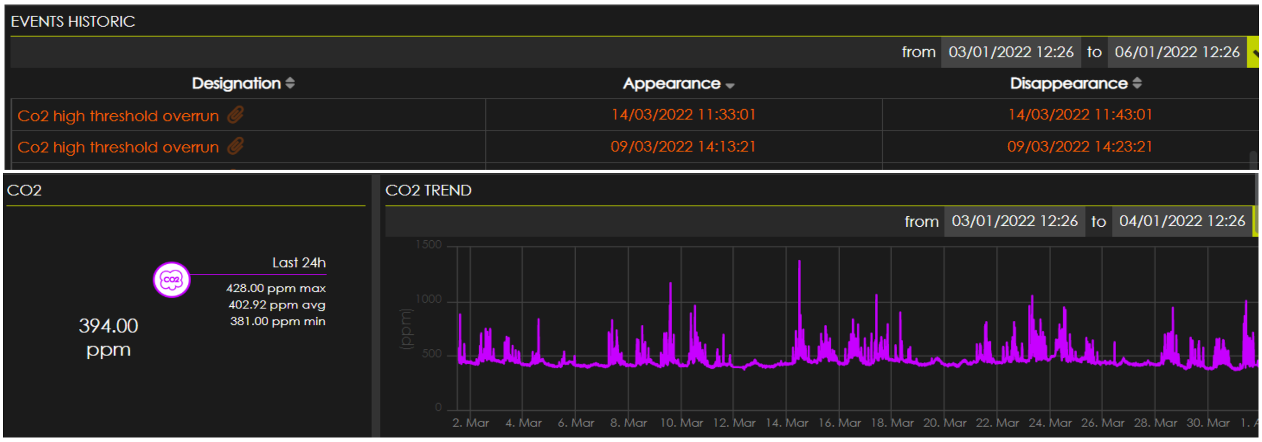
Figures 6a&b ALLIoT field test device and antenna extension

3.2 Air Quality

This device was located within the lift car and shows live data and can assist clients by providing information to tenants regarding the air quality within a lift car following the Covid-19 pandemic.

It was found that there is no standardised measurement for indoor CO2 levels that could be attributed as a ‘safe environment’, however, many indoor air quality (IAQ) professionals have adopted a value of 1000 parts per million (ppm) CO2 as a guideline for acceptable indoor air quality [11]. With this in mind, a high threshold of 1000ppm was set using the Kheiron dashboard settings.

The results show that, on average the lift had C02 measurements between 400-450ppm within the lift car. Over the three-month period between 1st March and 1st June 2022, there were six instances where the C02 levels were measured above the threshold, these were sporadic with regards to the time of day and did not follow any pattern. The values all returned to normal levels when the device took the next measurement (10 minutes later). If the CO2 levels had been persistently above the threshold, a manual or even automatic process could be implemented where the lift doors are opened, or a call placed in to force an air change and reduce any risks of virus spread.



Figures 7a&b Carbon dioxide measurements and above threshold notifications

This information is valuable to the building management companies and business owners, who can show the live data to their tenants and employees to reassure them that using the lift is safe, assisting with workers returning to offices.

This supports the statistic that 58% of employees reported feeling more comfortable if their employers used data to improve the healthiness of their buildings [12].

Measurements for temperature and humidity can also be taken from the same sensor and thresholds set to mitigate risks involved with virus spread along with improving overall passenger comfort.

3.3 PIR Sensor

In the UK, lift systems in commercial buildings are typically designed to guidance set out by the British Council of Offices (BCO) with the most recent guidance published in 2019 [13].

Table 1 BCO Guidance for lift performance in commercial buildings

Scenario	Handling Capacity (% of Population/5 Minutes)	Average Waiting Times (s)	Average Time to Destination (s)
Up-Peak	12%	≤25	≤90
		≤30	≤80
		<25	<110
Two-Way	13%	≤40	~

This sets the standard for lift performance; however, the Covid-19 Pandemic has changed the way in which the average office workers comes to work and employers are becoming increasingly flexible with working from home, staggering start times in the typical office and even trialling a national 4-day week pilot.

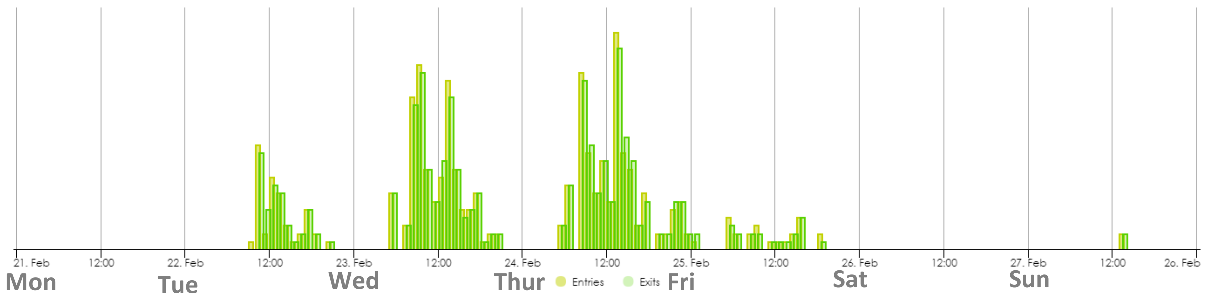


Figure 8 PIR sensor graphs showing people movement over a 1-week period

Table 2 Raw data provided by PIR sensor

Date Time	Entries	Exits
24/02/2022 07:00	0.00	0.00
24/02/2022 08:00	22.00	21.00
24/02/2022 09:00	12.00	13.00
24/02/2022 10:00	7.00	7.00
24/02/2022 11:00	11.00	11.00
24/02/2022 12:00	6.00	6.00
24/02/2022 13:00	27.00	25.00
24/02/2022 14:00	12.00	14.00
24/02/2022 15:00	10.00	11.00
24/02/2022 16:00	3.00	3.00
24/02/2022 17:00	7.00	6.00
24/02/2022 18:00	0.00	0.00

The PIR sensor device is set up to collect data and send back to the server a summary of the number of people entering and exiting the lift over a period of 1 hour. As the BCO recommendations are based on a peak 5-minute period, we can configure the device to take measurements in 5-minute intervals by adjusting the frequency of measurements. Devices can be put on each landing entrance which will help with creating an accurate passenger movement template in a specific building and also produce average waiting times and times to destinations.

This information coupled with surveys of the perception of lift performance from tenants can help understand if office users are willing to accept higher waiting times than the average of 25-30s. In turn, this could have a significant impact on how buildings are developed in the future. With potentially fewer lifts being required, developers and design teams will benefit from lower embodied and operational carbon from the VT system.

Existing buildings can also benefit from lower operational carbon if the data is used to pinpoint downtimes in lift usage and then isolate an appropriate number of lifts. This could also be used in tall buildings to produce energy by making use of Lift Energy Storage Technology (LEST) achievable by automatic transport of bags of sand throughout the building. [14].

3.4 Energy Monitoring

The requirement for measuring and reducing operational carbon is becoming prevalent in an era where the world is setting stringent Net Zero targets. In order to assist in achieving these targets, IoT sensors can be applied to measure the real time energy usage of lift systems.

Figure 9 ALLIoT Energy Meter Dashboard Example

The sensor used was originally measuring power consumption every 15 minutes which was not providing a truly accurate picture of the lift energy usage. The software was updated on the device to measure every 1 minute to improve the accuracy of the measurements. This provided more accuracy but has a significant impact on the battery life of the sensor and also relies on the lift using energy when the measurement takes place.

Other methods of measuring real time energy usage were investigated and established that Eastron meters could be used to provide a constant energy reading rather than a sample taken at certain intervals. Eastron meters can connect to the LoRaWAN network and are also powered by the supply itself, removing the need for batteries.

Figure 10 LoRaWAN Eastron meter

Overall, these sensors will provide accurate measurements that can be used to strategically isolate lifts where necessary.

3.5 Light Sensor

This sensor was applied to the lift system to identify when the shaft lights have been left on. The dashboard provides an indication when the shaft lights are on or off.

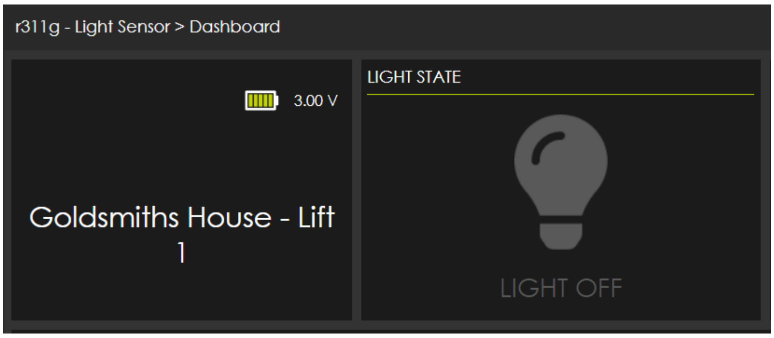


Figure 11 ALLIoT Light sensor dashboard example

With many maintenance regimes being monthly, shaft lighting left on could go unnoticed for some time. This system could notify when this has been left which can prompt someone to attend and turn them off, saving a considerable amount of energy as many lifts do not use energy efficient bulbs/LEDs in the shaft.

3.6 Water Sensor

The water sensor used within this study was placed in the lift pit and aimed to tackle environmental issues relating to flooded lift pits. Flooded lift pits were highlighted as number 12 in the top reasons for callouts in a study undertaken over a 13-month period that analysed 829 total calls across 114 lifts. This issue accounted for 2% of all calls (18 callouts) [10].

Figure 12 ALLIoT water sensor dashboard example

The UK has an average callout rate of over 4 calls per anum due to equipment failure [15]. With this in mind, ingress of fluid in lift shafts can be seen as a significant environmental issue. Various tests are typically required to identify the type of liquid found and to identify the source. An IoT system can be used to assist and highlight where the issues lie to remedy and proactively pump/clean the pits before it requires isolation.

Further development can interface devices with a sump pump to automatically remove the liquid [16].

4 FURTHER WORKS

Further works that the author would like to investigate to enhance the findings of this study are detailed below:

- Trial the LoRaWAN devices on other lift types.

- Update the PIR sensor software to improve the information and compare data with current recommendations for lift performance.
- Test Eastron meters to receive accurate energy readings of VT Systems and pair with other devices to produce strategies where lifts can be isolated to save energy or utilised for energy production in periods of downtime.
- Investigate automatic pit pumping devices that provide notifications to allow visibility of reoccurring problems.

5 CONCLUSION

Lift suppliers are providing IoT systems to assist with maintenance-related items and decrease the number of visits required, reduce the number of callouts, and provide transparency of the service provided to Clients.

Independent suppliers are just starting their IoT journeys with trials on third-party devices. This is being led by Client requirements for targeted maintenance regimes.

There is a gap in the market for the use of these devices to assist with: the design of VT systems, the comfort of passengers in a post covid world, the reduction of embodied and operational carbon emissions to meet global net zero targets and environmental issues regarding pit flooding.

REFERENCES

[1] Smith, G. (2015). From 1982 Coca-Cola vending machine to latest trend: What the Internet of Things means for business - Real Business. [online]. Available at: https://realbusiness.co.uk/from-1982-coca-cola-vending-machine-to-latest-trend-whatthe-internet-of-things-means-for-business/ [Accessed 15 May. 2022].

[2] Postscapes. (2018). Internet of Things (IoT) History | Postscapes. [online] Available at: https://www.postscapes.com/internet-of-things-history [Accessed 15 May. 2022].

[3] Serozhenko, M. (2017). Brief History of the Internet of Things – MQTT Buddy – Medium. [online] Medium. Available at: https://medium.com/mqtt-buddy/brief-history-of-theinternet-of-things-f00043ae17b5 [Accessed 15 May. 2022].

[4] Brown, R. (2019). The best smart home devices of 2019. [online] CNET. Available at: https://www.cnet.com/news/the-best-smart-home-devices-of-2019-amazon-alexagoogle-assistant-apple-homekit-video-doorbell/ [Accessed 15 May. 2022].

[5] Otis (2016). Elevator Company Otis Gets Lift from Technology | AT&T Customer Stories. [video] Available at: https://www.youtube.com/watch?v=vvhqPOu5vok [Accessed 23 June 2022].

[6] Schindler (2017). Schindler Builds an Internet of Elevators. [video] Available at: https://www.youtube.com/watch?v=ig45xleb4dE&t=7s [Accessed 23 June 2022].

[7] ThyssenKrupp (2016). The Internet of Things gives the world's cities a major lift. [video] Available at: https://www.youtube.com/watch?v=HMx0XiM5lvI [Accessed 23 June 2022].

[8] Kone (2017). IBM and KONE: Watson IoT Gives Lift to Innovation in Smart Buildings. [video] Available at: https://www.youtube.com/watch?v=EVbd3ejEXus [Accessed 23 June 2022].

[9] WeMaintain (2021). WeMaintain, the fast-growing PropTech company. [video] Available at: https://www.youtube.com/watch?v=5pHF4mzSYHA [Accessed 23 June 2022].

[10] Clements, P., 2019. The use of IoT technology to enable earlier identification and monitoring of faults on lifts. MSc. University of Northampton.

[11] Eykelbosh, A., 2022. Can CO2 sensors be used to assess COVID-19 transmission risk? | National Collaborating Centre for Environmental Health | NCCEH - CCSNE. [online] Ncceh.ca. Available at: https://ncceh.ca/content/blog/can-co2-sensors-be-used-assess-covid-19-transmission-risk [Accessed 23 June 2022]

[12] InfoGrid, 2022. THE HYBRID WORKPLACE. The Return to Work Report. London.

[13] British Council of Offices (2019), Guide to specification. Unknown: Various.

[14] Hunt, Julian David and Nascimento, Andreas and Zakeri, Behnam and Jurasz, Jakub and Dąbek, Paweł and Barbosa, Paulo Sérgio Franco and Brandão, Roberto and Castro, Nivalde José and Leal Filho, Walter, Lift Energy Storage Technology: A Solution for Decentralized Urban Energy Storage. Available at SSRN: https://ssrn.com/abstract=4032342 or http://dx.doi.org/10.2139/ssrn.4032342

[15] Mitsubishi (2019) Home Page - Reliability and Maintenance [online] Available at http://lifts.mitsubishielectric.co.uk/ [Accessed 20 June. 2022].

[16] Kolakovic, M. (2018). Build the IoT Sump Pump (or Pretty Much Anything IoT). Nuts and Volts. Feb.

BIOGRAPHICAL DETAILS

Paul started his career in D2E as a Graduate Engineer. He has been with D2E for 8 years' and has experience largely in commercial and leisure sector, working on multiple portfolios across the UK and providing project assurance for lift replacement and modernisation projects.

In 2020, Paul moved from the Portfolio Team into the Design Team and has since worked on various key developments within D2E, predominantly in London.

Paul has achieved Masters in Lift Engineering at the University of Northampton and works towards his Chartered Engineer status (CEng) with Chartered Institution of Building Services Engineers (CIBSE).

The Investigation of Efficacy and Fire Resistance Characteristics of Fire Barrier in the Lift Industry Applications

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Keywords: Landing door, Hoistway, CFD, Fire Rating, Composite.

Abstract. Although it would be preferable for the lift well to be located in the fire-protected area of the building, it is not always possible. Therefore, most newly installed lifts are required to have adequate fire resistance for the length of time corresponding to the fire rating of the building in which they are fitted. The national and international regulations specify such fire rating requirements. However, the regulations fail to address the scenarios that involve lift service or installation periods. In most cases, the lift shaft is then fully or partially open with an exposed area of the entrance creating a significant hazard in time of a fire. In this paper, a novel solution is presented to this problem by considering the design standards, regulations and fire resistance testing procedures. The flow simulation and computational fluid dynamics software are used to simulate and validate the suitability of the proposed solution. It is shown that the development of a temporary fire barrier covering the lift well is feasible. However, further testing and full certification are needed to produce a final, commercially viable product.

1 INTRODUCTION

When designing a hoistway with all its components, multiple factors are taken into consideration. The material of door leafs, the architraves, and the other components associated with the lift entrance must be chosen and engineered with strength, longevity, and fire protection in mind. Fire protection is most commonly achieved by using components with known fire resistance and insulation properties. As most of the lift panel components are made of sheet metal, specialised techniques are used to account for and, in some cases, take advantage of metal thermal expansion. For example, when heated by fire, a door panel jams itself in between the sill and top header, sealing any previous gaps at the bottom and the top area. Another instance is the use of overlapping smoke fillets to prevent the formation of excessive gaps between panels (Fig. 1).

British and international regulations form a series of standards concerning the safe design and testing of passenger and goods passenger lifts [1–3]. Therefore, if the lift construction fire rating is certified and fully compliant with the building fire regulation, it becomes part of the building fire rating [2], [4], [5]. In other words, the whole building's fire rating is compromised if the lift entrance is no longer fire-protected.

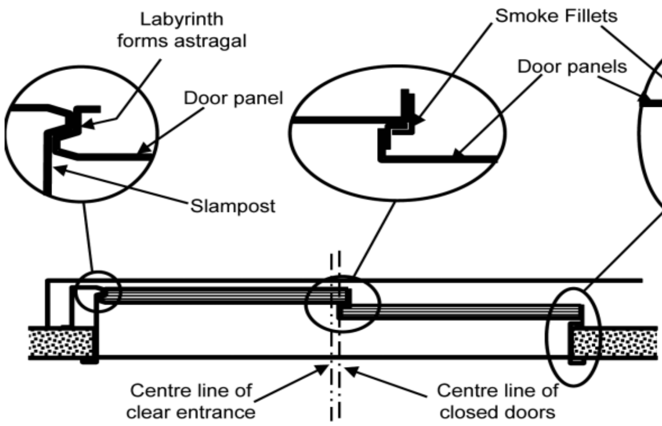

Figure 1 Smoke Fillets

Amongst many aspects, the stack effect, also known as the "chimney effect", is one of the most dangerous fire propagation phenomena when the lift shaft entrance fire resistance is compromised. This happens primarily while the lift entrance is being serviced or during its installation when part or the whole of the hoistway is open. Although it is most prominent in tall multi-story buildings, its impacts can be observed even in the two or three floor lift shafts [6]. In principle, the stack effect occurs when high-temperature gases rise inside the lift shaft, causing a change in the pressure relative to the neutral pressure plane [7]. As a result, it generates movement of the air in the lift shaft, changes the density of the air inside it and, in many cases, sucks in the fresh air into the fire room.

This paper looks at the current applicable construction and fire regulations and testing methods. It explores possible methods of developing the temporary fire barrier and using the simulation software to analyse the fire propagation thwarting characteristics of the found solution.

2 STANDARDS, FIRE TESTING AND SIMULATION SOFTWARE

2.1 Regulations

In the UK, the primary standards employed in the lift industry relevant to this study are EN 81-20[2] and EN 81-58[3], with EN 81-50[1] and EN 1634[8]/ BS EN 1363-1[9] defining testing procedures to implement them accordingly.

EN 81-20 sets out safety requirements for construction and installation, while EN 81-50 sets out test and examination requirements for specific lift components. In addition, the standards contain several requirements with the aim of improving passenger safety.

The landing and car door section of EN 81-20 (paragraph 5.3) explicitly defines rules on how the door should be designed and installed, with details ranging from the dimensions and clearances to its mechanical strength and movement. In this regulations segment, we learn that the strength of the landing door must be assessed with static load and a pendulum shock test with the given criteria for acceptance. We can also find the critical rule concerning the fire safety of the door. The section defining door behaviour under fire conditions states, "Landing doors shall comply with the regulations relevant to the fire protection for the building concerned. EN 81-58 shall be applied for the testing and certification of such doors"[2].

Most manufacturers have adopted EN 81-58 fire test methods with the corresponding testing procedures of EN 1634 as it allows the door design to be recognised as suitable in all European countries. The typical duration of the fire-resistance rating is 30, 60, 90, and 120 minutes, with most manufacturers aiming for the two-hours rating as standard.

Criteria of performance as defined by the EN 81-58:

Integrity (E) - The main criterion for judging the performance of the test specimen is the integrity. For lift landing doors, as long as the leakage rate per meter width of the door opening does not exceed 3.0 $m^3/(min \cdot m)$, the integrity criterion is satisfied. This is not taking into account the first 14 minutes of the test.

Thermal insulation (I) - If insulation requirements apply, the insulation criterion l is no longer satisfied when the average temperature rise exceeds 140 K. The maximum temperature rise on the door leaf, over panel and side panel with a width ≥ 300 mm shall not exceed 180 K.

Radiation (W) - If radiation requirements apply, the radiation criterion is satisfied until the measured radiation exceeds the value of 15.0 kW/m^2, measured as specified in EN 1363-2[9].

Direct field of application:

Test results in terms of Integrity (E) and Thermal Insulation (I) are considered to be applicable to doors of sizes different from those of the test specimens, all other constructional details being the same, within the following limitations:

- without correction to be applied on the measured leakage rate.
  1. a similar door of lower height than the tested specimen.
  2. a similar door with a door opening or an opening width in the wall equal to the one tested within a range of +/- 30%.
- after correcting the measured leakage rate as a function of the increase in height, as specified in "Interpreting the leakage rate curve".
  1. a similar door with an increased height of up to 15%.

Criteria of performance as defined by the EN 1634[6]/ BS EN 1363-1[7]:

Integrity (E) – Unless otherwise specified in the relevant test method, the integrity of separating elements shall be evaluated throughout the test by cotton wool pads, gap gauges and monitoring the test specimen for evidence of sustained flaming.

Gap gauges -

a) whether the 6 mm gap gauge can be passed through the test specimen, such that the gauge projects into the furnace, and can be moved a distance of 150 mm along the gap; or

b) whether the 25 mm gap gauge can be passed through the test specimen such that the gauge projects into the furnace.

Thermal insulation (I) - If insulation requirements apply, the insulation criterion l is no longer satisfied when the average temperature rise exceeds 140 K. increase at any location (including the roving thermocouple) above the initial average temperature by more than 180 K.

Direct field of application:

Unlimited size reduction is permitted for all types except insulated metal doors where a reduction to 50% width and 75% height of the tested specimen is the limit of variation. The size increase is permitted only for those which are required to satisfy integrity or integrity and insulation and then only up to:

- 15% height, 15% width and 20% area

Considering the above, when designing the temporary fire barrier, it is clear that not all of the rules applicable to the permanent hoistway construction are transferable. Consequently, if the solution is to be deployed within a short time and made easy to use, some compromises must be made. Therefore, priority is given to the fire safety and strength of the entrance gate. Thus, creating a physical barrier capable of stopping anyone from falling into the shaft, preventing access to the lift shaft for an unauthorised person, and being able to withstand 120 minutes fire scenario are the main objectives which are considered to develop the prototype.

2.2 Fire testing, preparation and procedures

A number of scaled-down components have been tested in the glow plug laboratory furnace (Fig. 2) in preparation for the official fire testing. The process eliminated the unsuitable components and narrowed down the list of the most appropriate materials. It became clear that composite materials offer the best possible solution. The construction with only metals leads to very high levels of thermal expansion, increases weight and adds difficulty and complexity to secure the structure in place under fire conditions.

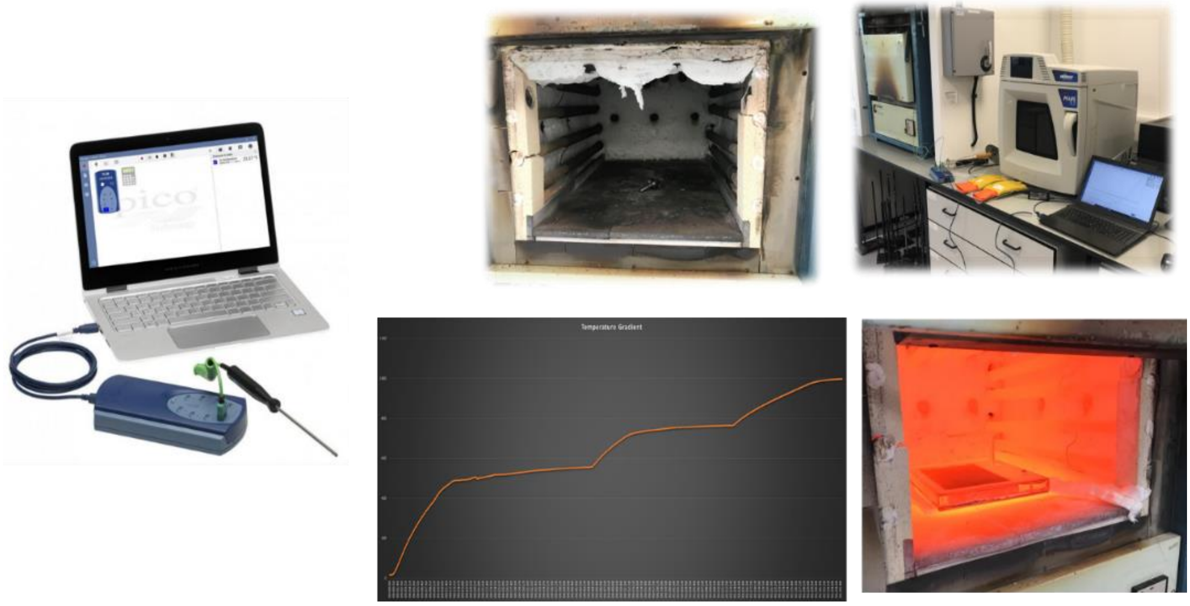

Figure 1 Testing of scaled-down components

Figure 2 Furnace Fire Testing

Lift landing doors are tested from one side only, unlike regular fire doors. In principle, the landing door specimen is mounted into a furnace wall. As the fire penetration is tested inwardly into the shaft, the landing side of the door set is the part facing the fire while in the controlled furnace. Figure 3 shows prototype fire testing at the BRE Global facilities. The temperature inside the furnace follows a specific heating curve given by the logarithmic function which is shown in Fig. 4.

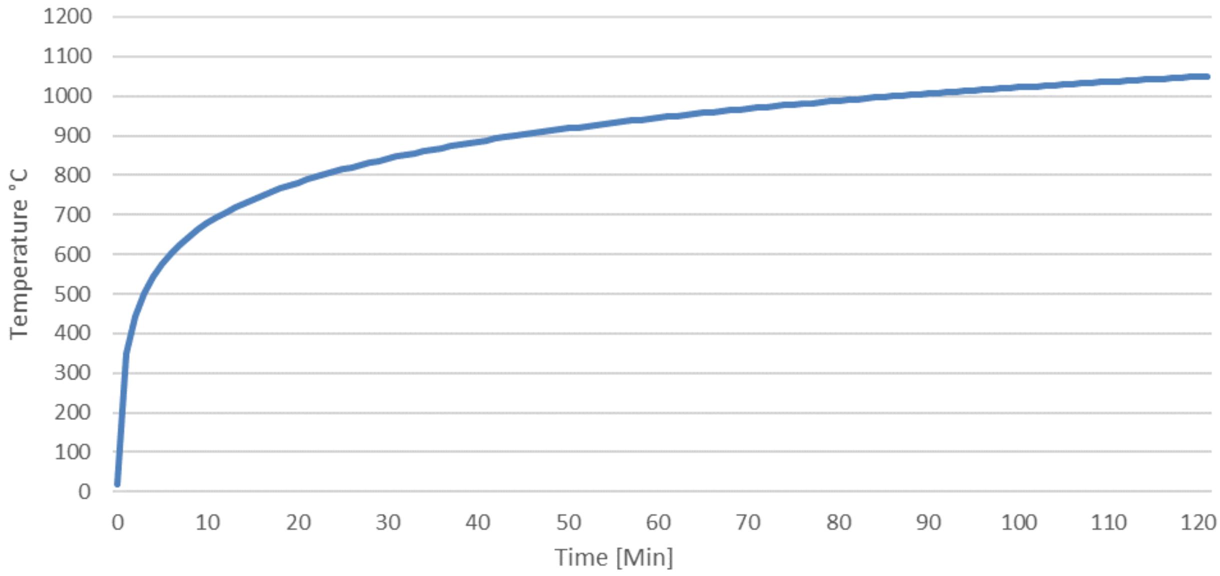

Figure 3 Temperature/Time Curve

The relationship between the average furnace temperature *T* and time *t* follows (Eq. 1):

$$T = 345 \log_{10} (8t + 1) + 20. \quad (1)$$

A set of thermocouples is deployed to monitor the temperature on the door's surface, and the data is saved for later analysis. Regular visual evaluations are performed throughout the test, and probe testing is performed if any potential gap development is spotted. The door set passes the Integrity (E) test if the number and size of gaps around the entrance do not exceed a specified limit [8].

2.3 Use of Ansys Fluent as simulation software

Ansys Fluent is used as the platform for numerical simulation. Its Computational fluid dynamics (CFD) code capabilities allow for modelling fluid flow, turbulence, heat transfer, mass transfer, and chemical reactions [10]. Manufacturers commonly use it to test design ideas and prototypes. The software is part of the Ansys products range, and its application capabilities are broad, as described above. Since the early 1930s, CFD techniques have been used extensively in the design and analysis of engineering systems, with simplified calculations executed by scientists and engineers. Initially, fluid flow calculations were limited to 2 dimensional due to the lack of computational power. However, the advancements in technology and software made the use of simulation tools like Ansys more powerful and essential to designing a new product.

The data collected during the full-scale fire testing, combined with the temperature and physical behaviour information of particular components gathered in the small-scale furnace tests, would be used to validate the CFD model. Once the model is defined and validated, then it can be used to simulate different scenarios in various building combinations.

3 CONCLUSION

In this research, it is shown that the development of the temporary fire safety-compliant hoistway barrier is feasible. From the initial findings, it can be concluded that the composite materials offer the most appropriate solution for the prototype. The composite materials used in this work present reliable strength and fire resistance properties while maintaining a low weight. However, further investigation is required to finalise the product design and overcome manufacturing limitations. In addition, full compliance with the regulations and successful fire rating tests are essential factors before it can be brought to the market.

REFERENCES

[1] British Standards Institution, BS EN 81-50 Safety rules for the construction and installation of lifts. Examinations and tests. Part 50: Design rules, calculations, examinations and tests of lift components. 2020.

[2] British Standards Institution, BS EN 81-20 Safety rules for the construction and installation of lifts. Lifts for the transport of persons and goods. Part 20: Passenger and goods passenger lifts. 2020.

[3] British Standards Institution, BS EN 81-58 Safety rules for the construction and installation of lifts. Examination and tests. Part 58: Landing doors fire resistance test. 2018.

[4] The Building Regulations 2010, 'The Building Regulations 2010 - ADB Vol1 Dwellings 2019 edition inc 2020 amendments'. The National Archives, 2020. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/937931/ADB_Vol1_Dwellings_2019_edition_inc_2020_amendments.pdf

[5] The Building Regulations 2010, 'The Building Regulations 2010 - ADB Vol2 Buildings other than dwellings 2019 edition inc 2020 amendments'. The National Archives, 2020.

[6] Y. Li, H. Sun, and X. Shan, 'Effect of shaft height on smoke control in tall building fires', IOP Conf. Ser. Earth Environ. Sci., vol. 227, p. 042017, Mar. 2019, doi: 10.1088/1755-1315/227/4/042017.

[7] W. Shi, J. Ji, J. Sun, S. Lo, L. Li, and X. Yuan, 'Experimental Study on the Characteristics of Temperature Field of Fire Room under Stack Effect in a Scaled High-rise Building Model', Fire Saf. Sci., vol. 11, pp. 419–431, 2014, doi: 10.3801/IAFSS.FSS.11-419.

[8] British Standards Institution, BS EN 1634 Fire resistance and smoke control tests for door and shutter assemblies, openable windows and elements of building hardware. 2021.

[9] British Standards Institution, BS EN 1363-1 Fire resistance tests. Part 1: General requirements. 2020.

[10] 'Ansys Fluent | Fluid Simulation Software'. https://www.ansys.com/en-gb/products/fluids/ansys-fluent (accessed May 25, 2022).

BIOGRAPHICAL DETAILS

Mateusz Gizicki has a bachelor's degree in mechanical engineering from the University of Northampton and is currently working towards achieving his doctorate in the area of multi-physics and computational fluid dynamics. He is a member of the Institution of Mechanical Engineers. He has experience in research and development in the industry environment as well as academia. In addition, he has recently completed the Knowledge Transfer Partnership project, which combined management skills with complete product development as an associate.

Stefan Kaczmarczyk has a master's degree in Mechanical Engineering and he obtained his doctorate in Engineering Dynamics. He is Professor of Applied Mechanics and Postgraduate Programme Leader for Lift Engineering 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. Professor Kaczmarczyk has published over 90 journal and international conference papers in this field. He is a Chartered Engineer, being a Fellow of the Institution of Mechanical Engineers, and he has been serving on the Applied Mechanics Group Committee of the Institute of Physics.

Brian Henderson has made elevators a career having been in the Lift Industry while completing a dual trade apprenticeship with EPL KONE in Australia over 35 years ago. Winner of the Australian Apprentice of the Year in 1990, he subsequently worked internationally with KONE and its subsidiaries. His keen interest in business resulted in multiple new start business operations in Australia, Asia, the UK and the EU covering a number of industries. One of those businesses was Elevator Engineering Services UK Ltd which enters its 20th year of operations in 2023, providing research, development, engineering and manufacturing solutions to the medical, food, automotive and lift industries amongst others and also developed the KTP project subject matter.

Neil Clark has 28 years of experience in Fine Limit Sheetmetal work. He worked for several years in control panel manufacturing and the lift Industry. Joined EES UK Ltd in 2009 as a workshop supervisor and helped to bring all the EES UK's manufacturing 'in-house'. He currently holds the production manager position, overseeing design, manufacturing and production. He specialises in finding and implementing bespoke fabrication solutions for customers from various industry sectors, ranging from lifts and escalators, motorsport, construction, and food packaging to control panels.

Dr Rasoul Khandan’s work experience in higher education span over 15 years with a specific interest in Mechanical and Manufacturing Engineering. Currently, he is the programme director of MSc Professional Engineering at Aston University. Before joining the University of Aston in December 2021, he was a Senior lecturer in the Technology department at University of Northampton for over 4 years. He has also worked in other higher education institutes such as Loughborough, Swansea and Bournemouth universities since 2008. Dr. Khandan's research interests are: Advanced and Digital manufacturing, Lean Manufacturing, Digital Twin and Industry 4.0.

IoT Safety Predictive Monitoring of Lift Operations, Shafts and Buildings

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Keywords: Safety, predictive maintenance, continuous monitoring, lifts, buildings

Abstract. The current market is lacking single reliable and cost-effective solutions for lift and building health monitoring systems that are suitable for both of them. A purposely designed safety device turning any lift into a building structural monitoring system that enables continuous remote monitoring and real-time diagnostic of both the operational status of lifts and health of building structures. A cloud-connected sensor package would continuously track variables like vibrations, accelerations, displacements, and other physical phenomena. The data gathered from specifically positioned sensors would be wirelessly transmitted to the cloud and screened via bespoke analytical software using reliable specific algorithms based on machine learning and cognitive computing. As a result, many lift or building anomalies can be detected in real-time. Users can receive alerts, notifications, and reports, through a dashboard, on smartphones, tablets, and PCs for further engineering analysis. This solution would allow lift companies and building owners to plan and act prior to breakdowns, damage, or accidents, subsequently reducing their financial costs in the medium/long terms (predictive maintenance). There are no potential disadvantages in combining lift monitoring with building monitoring and there is no risk of conflicts between building and lift maintenance contractors as the root cause of a threshold breach are differentiated by the two separate signals for lifts and buildings. The data analysis focuses on one or the other given the different frequencies responses. However, both collected data can easily be combined and provide additional information that would otherwise not be available. The reading combination of data would increase people's overall safety, optimize maintenance, improve performance, and protect the long-term value of assets. Buildings and lifts are also prone to a gradual ageing process. In accordance with EU Commission data, about 80% of the EU building stock is over 25 years old and people spend approx. 86.9% of their life inside buildings, including lifts. Additionally, all buildings are subject to hazards due to fast-growing urbanization and adverse nature, including earthquakes, landslides, floods etc. Progressive deterioration or defects of building structures and lifts are, in most cases, hidden and evolve unnoticed until a failure occurs. Currently, lift and building maintenance is based on several periodic inspections, resulting in high costs and low efficiency causing CO_2 dispersion. A purposely designed safety device can provide a solution to monitor lifts and buildings 24/7/365 remotely by using the lift shaft as a vector. A user-friendly solution which enables an accurate maintenance planning, therefore reducing the number of site visits to the ones needed, therefore minimising traffic and personnel on the road from making unnecessary site visits, helping to generate a more efficient ecosystem.

1 INTRODUCTION

Buildings and lifts are prone to a natural and gradual aging process. About 80% of EU buildings stock is over 25 years old. All buildings, including the new ones, are subject to hazards caused by human actions, fast-growing urbanization, and the natural environment including earthquakes, landslides, floods. Progressive deterioration/wearing and even damages or defects of building structures and lifts are, in most cases, hidden and evolve unnoticed until a failure occurs. Accidents, resulting from faults and critical events or disasters, occur. People spend around 86.9% of their life inside buildings and lifts. Home, office, school, hospital, shop, hotel are places to be kept safe! To date, stakeholders cannot have access to 24/7/365 information about the state of their assets and cannot monitor factors that can affect buildings and lifts making them unsafe until uninhabitable or inoperable. Statistics of human and economic losses are quite impressive. It is not a deferrable need.

This paper will take a brief look at how IoT remote continuous monitoring is the key to a worldwide digital transformation and modernization of buildings and lifts improving the resilience of cities by means of assessing and providing a diagnosis of buildings and lifts, aiming at decreasing critical events, protecting people’s life and real estate investments. Analysis of the data obtained enables predictive maintenance resulting in improved performance, greater reliability with less downtime, and a consequent increase in overall safety while reducing costs in the medium and long terms. An extended application in urban environments of an economically and socially sustainable solution can contribute to risk mitigation on a large scale making the world’s buildings/cities safer, more resilient, and more efficient.

Approx. 20 million lifts are installed worldwide, most of which before 1999, date when Directive 95/16/EC came into force. Now, they are in a state of technological obsolescence regarding energy and safety efficiency; additionally, buildings are at risk due to their ageing, natural and human threats. Prevention and safety requirements often struggle to climb the priority list of administrators in a world that constantly finds difficult economic balances. Market data indicates a strong trend in urbanization on a worldwide basis leading to the construction of approx. 13,000 new buildings a day between now and 2050; most of them built in urban areas requiring constant monitoring of potential risks affecting structural health.

Why now?

Structural health monitoring is today a complex and expensive service. In the absence of specific legislative rules that favor its adoption, it is planned to use lift predictive maintenance, which brings tangible economic benefits, as the strong driving force behind the introduction of a capillary system for monitoring the health status also of buildings for a safer, resilient, and efficient society. At present, on the market there is no cost-effective solution to bring old installations to a new life with the described features and peculiar characteristics.

The technological advancement of sensors, cloud computing, AI, machine learning, and the achieved quality of applicable scientific knowledge are such as to facilitate fast vision-design-prototyping-go-to-market processes. Even more, the issues addressed are current and in line with Europe's objectives for resilient cities (safety), circular economy (reuse of existing installations), accessibility (greater availability of installations) and energy-saving (fewer empty travels, general efficiency). All together the new trends of home or remote working are factors and prerequisites for the surfacing of latent and hitherto unmet needs. Statistics on damage related to accidents in lifts or due to the partial or total collapse of buildings are increasing. The latest reported events in Bordeaux and Miami confirm that buildings are extremely vulnerable, structures that must be monitored in an effective way. There is a definitive need for a solution that can raise the risk awareness and improve the assessment with new diagnostic capabilities for lifts and buildings.

2 CONTINUOUS REMOTE MONITORING AND REAL-TIME DIAGNOSTICS OF BOTH BUILDING STRUCTURES HEALTH AND LIFTS OPERATIONAL STATUS.

2.1 IoT monitoring solutions: Basics

A cloud-connected sensor package continuously tracks variables like vibrations, accelerations, displacements, and other physical phenomena. The data from the sensors are wirelessly transmitted to the cloud and screened via bespoke analytical software using reliable specific algorithms based on machine learning and cognitive computing. In this way, anomalies can be detected in real-time. Users can receive alerts, clear notifications, and reports on smartphones, tablets, and PCs and gather buildings and lifts data remotely, ready to be aggregated for further analysis, all through a customizable and user-friendly dashboard.

2.2 What are the existing solutions and what are their limits?

The maintenance of lifts is often limited to periodic codified checks, a preventive maintenance logic that while raising the standards of safety and reliability, is not very efficient especially as it does not consider the real use of the lift. A time-frequency that cannot guarantee maximum safety and efficiency. Interventions are often carried out only when failures and accidents occur. Solutions currently on the market are all aimed at implementing, at different levels, lifts monitoring systems only where suppliers of electronic boards interface with the lift controller allowing to remotely view only some data of the operating status and others that, thanks to the installation of sensors, can measure in more depth the state of wearing of specific components.

2.3 Why is the proposed solution new compared to the existing solutions?

The proposed solution makes use of the latest technological standards provided by the up-to-date generation of "MEMS" sensors, a cloud platform with proprietary machine learning algorithms. "MEMS" are extremely less expensive than other types of sensors (e.g. “FE” piezoelectric sensor) and provide sufficient response for a first level analysis (alarm threshold) for a more in-depth follow-up (especially for buildings). Unlike others, the proposed solution works on any lift, being in fact an independent chain that does not invalidate the warranty or safety of a lift, is easily installed by the lift maintenance people and is activated through a convenient subscription. The main innovative feature is that to date there are no other remote lift monitoring solutions incorporating, in a single installation, also the remote monitoring of changes in the structural state of a building. It is important to measure the impact of different threats in all phases of the building's life to determine its structural health, which becomes a fundamental requirement to consider for raising the level of safety of the "lift-building-people" ecosystem. The use of the lift shaft as a mean of collecting lift and building data provides strong advantages: economic, technical and practical implications resulting in lowering costs, less invasive and safer installations compared to other solutions on the market while providing a richer amount of data, available for further analysis.

2.4 Why is a significant improvement of something existent?

The proposed remote continuous monitoring solution represents a significant improvement in the maintenance service process for buildings and lifts in a new and existing applications environment. Analysis of the data obtained enables predictive maintenance resulting in improved performance, greater reliability with less downtime and a consequent increase in overall safety, while reducing costs in the medium and long terms. The rich data obtained with the proposed application is extremely useful as it can improve the overall diagnostic capabilities of the entire ecosystem over time. This is the core value of this innovation: to transform any lift into a tool for monitoring the structural health of a building with overall benefits for energy efficiency, accessibility and safety.

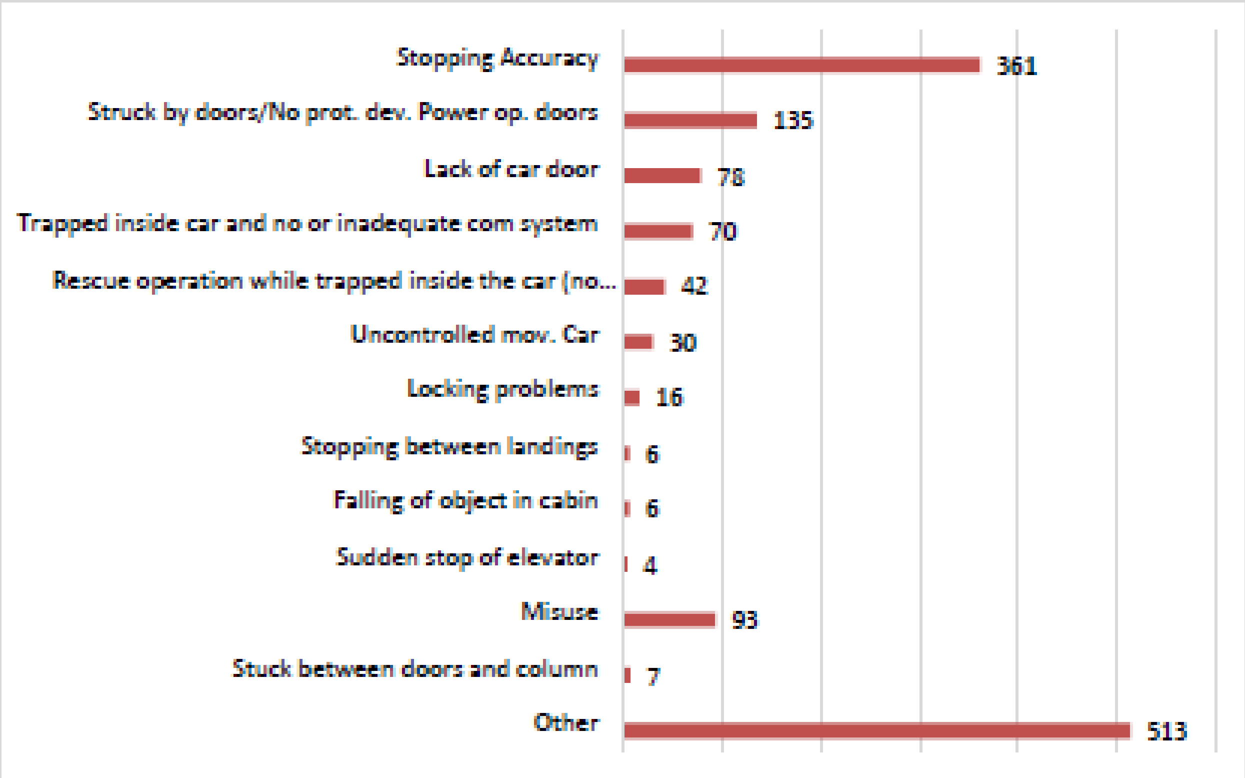
A building and lift “combined” monitoring system can help correlate the effects of the building to the lift and of the lift to the building. In this way it is possible to identify the cause / effect generating a malfunction by attributing objective responsibilities either to the lift system/maintenance or the building structural behaviour.

To date, a study or research on the correlation between buildings and lifts' mutual interactions has not been produced. Therefore, the combined monitoring of buildings and lifts can be of help to identify the root causes of problems generated.

A study done by Hitachi has shown that an earthquake caused the shutdown of 15,000 lift installations resulting in an approx. over a thousand, highlighting the need for strong maintenance/replacements while indicating the necessity for capillary monitoring, as it took a long time for surveying and repairing. A punctual monitoring of the building before and after an event allows a timely survey of the state of the building itself and consequently of the lifts by identifying any post-event structural deformations that may have affected the lift systems.

Thanks to continuous and punctual monitoring, it is possible to understand the behavior of the building and the problems that this can cause to the lifts, and also identify, on a statistical basis, the most frequent anomalies that can be generated over the years.

Official reports from independent bodies (ELA) and companies have shown that in recent years the majority of the lifts' accidents are due to:



Are these problematics caused by poor maintenance, errors during installations or building movement effects? Proper, easy monitoring is aimed at intercepting, in advance, the root causes.

2.5 The benefits

Since rapid urbanization and population growth will drive to a large extent the impact of human and natural hazards on buildings, stakeholders will need to better understand building and lift behavior and their health status. A platform that helps stakeholders making decisions, planning adequate intervention before serious damages occur, avoiding both accidents and money losses (predictive maintenance) or after critical events like an earthquake. This ultimately allows for smarter decision-making, thanks to improved awareness. The aim is to impact the market with high-quality, efficient and cost-effective digital technology that improves the safety of buildings and lifts, reducing overheads in a challenging economy, notifying potential problems before they result in damage or failure or worse in accidents, minimizing downtime costs, improving the overall performance, maximizing product life and utilization and preserving asset value over time while helping to manage emergencies after a critical event. Insurance companies may introduce "building black box" solutions enabling the monitoring of critical elements to offer the market a parametric insurance model.

3 MONITORING PLATFORM: THE PROJECT COMPONENTS

- **Sensors:** The hardware is designed with state-of-the-art of sensors, based on "MEMS" technology, including triaxial accelerometers and inclinometers. Additional sensors are used to measure physical quantities such as noise, temperature, humidity, etc. "MEMS" sensors have reduced dimensions, continuous monitoring (24/7/365) and are connected between each other forming a chain. They are located strategically along the lift shaft: on the lift guide rail, on top of the lift cabin and in the pit.

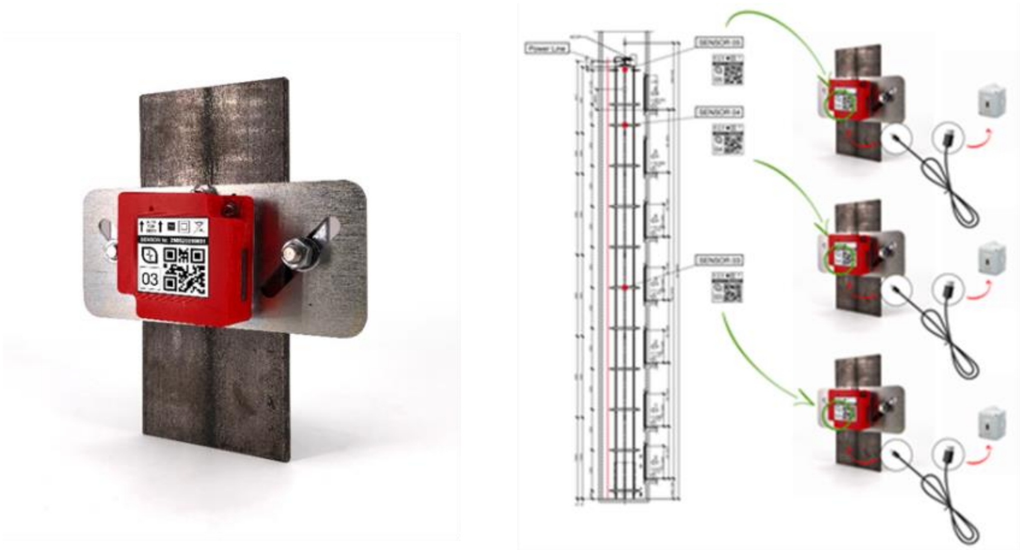
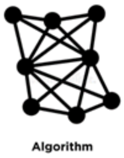


Figure 1 Typical sensors application

- **Algorithms**: Algorithms perform different functions in building safety applications. The large quantity of data coming from sensors are hedge computed among those to be sent to the cloud. In-house developed algorithms represent the most crucial part of the project since they generate valuable information out of big data. Algorithms analyse vibrations, accelerations and displacements and carry out diagnostics in order to assess the health of the system, and send alarm signals in a preventive manner. These algorithms, being specifically embedded, translate the data received into useful indicators and provide a visual representation on a dashboard.



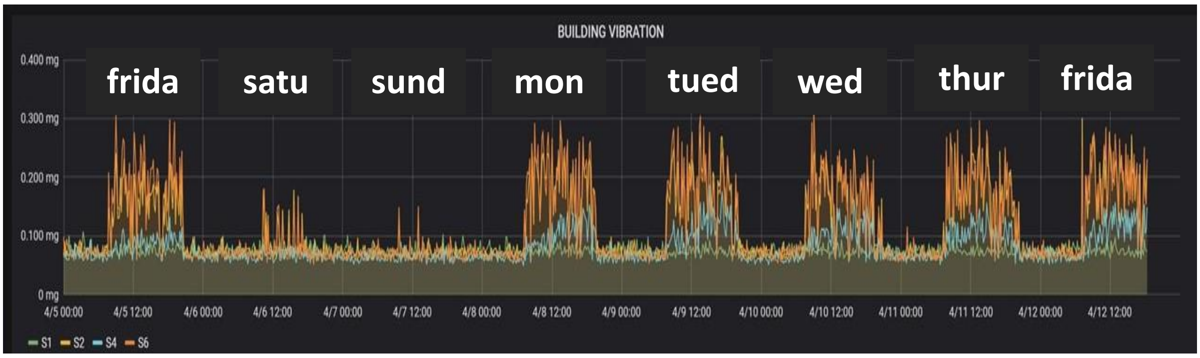


Figure 2 Typical sensors analysis out of Algorithms

- **Gateway**: Data collected by the sensors are transmitted to a gateway for analysis and filtering and then transferred to the cloud. A gateway is connected to the chain of sensors through dedicated cables and filters**.** A huge amount of data flows from the sensors, which is analysed locally by suitable algorithms, thus extracting synthetic indicators. In this way, only much smaller amounts of information are sent to the cloud than the amount of raw data collected by the sensors. The gateway includes a specific in house developed firmware for the electronic devices, communication protocols among different modules optical fibre/2G/3G/4G/5G and custom algorithms.

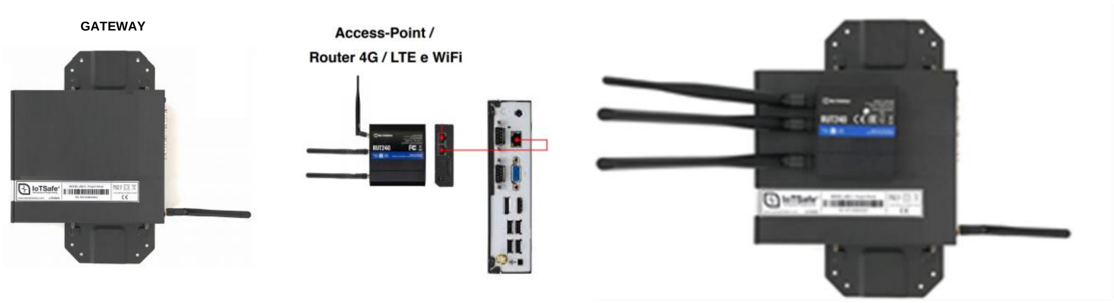


Figure 3 Typical transmission system

- **Cloud platform**: The constant and continuous transmission of data is possible through a different kind of connectivity. Data is treated in an advanced cloud platform, on which in-house powerful algorithms for analysis have been implemented, making use of cognitive computing. More specifically, the cloud receives data from the gateway, runs deeper analysis using cognitive computing and sends outputs to the front-end dashboard.

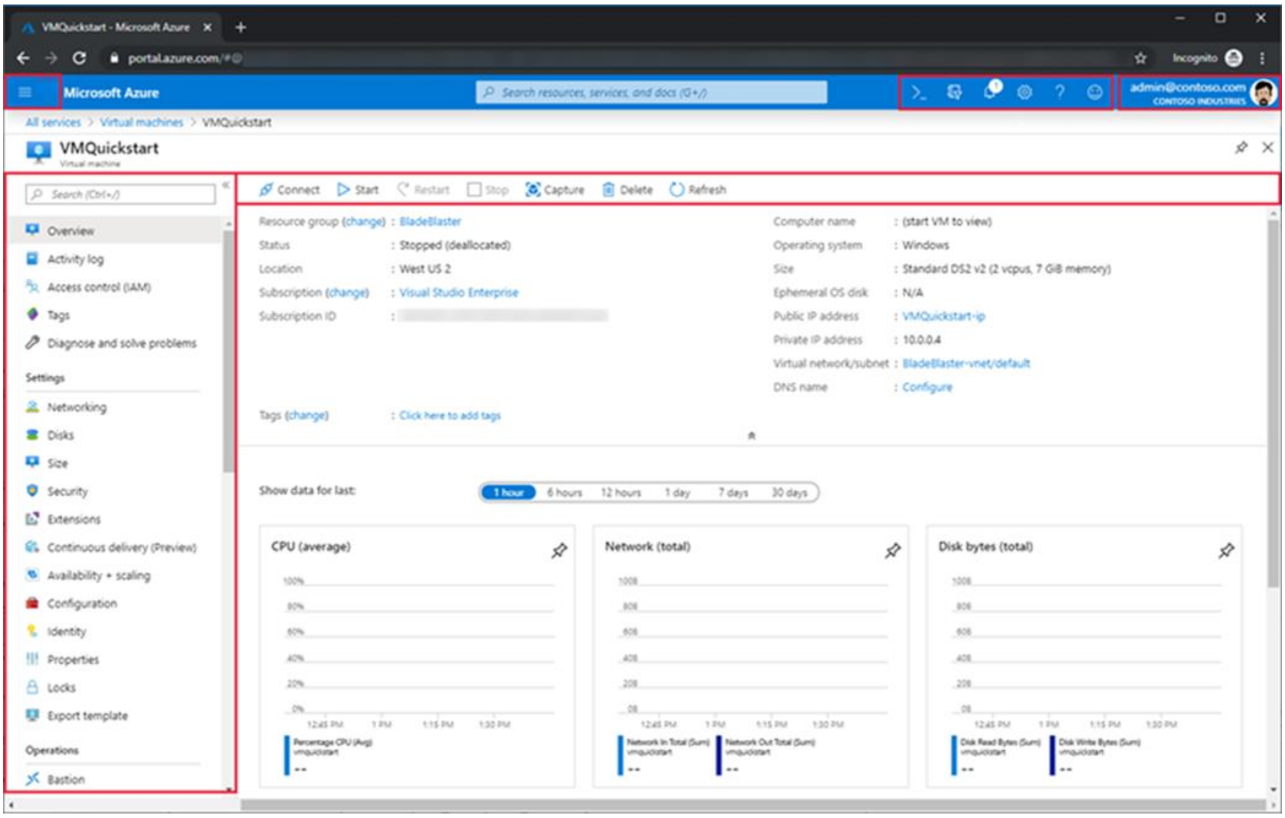


Figure 4 Typical Cloud representation

- **Dashboard**: The most relevant information is presented visually through a user-friendly dashboard, accessible through any modern electronic device. This can be customizable according to the contracted services and on customer preferences.

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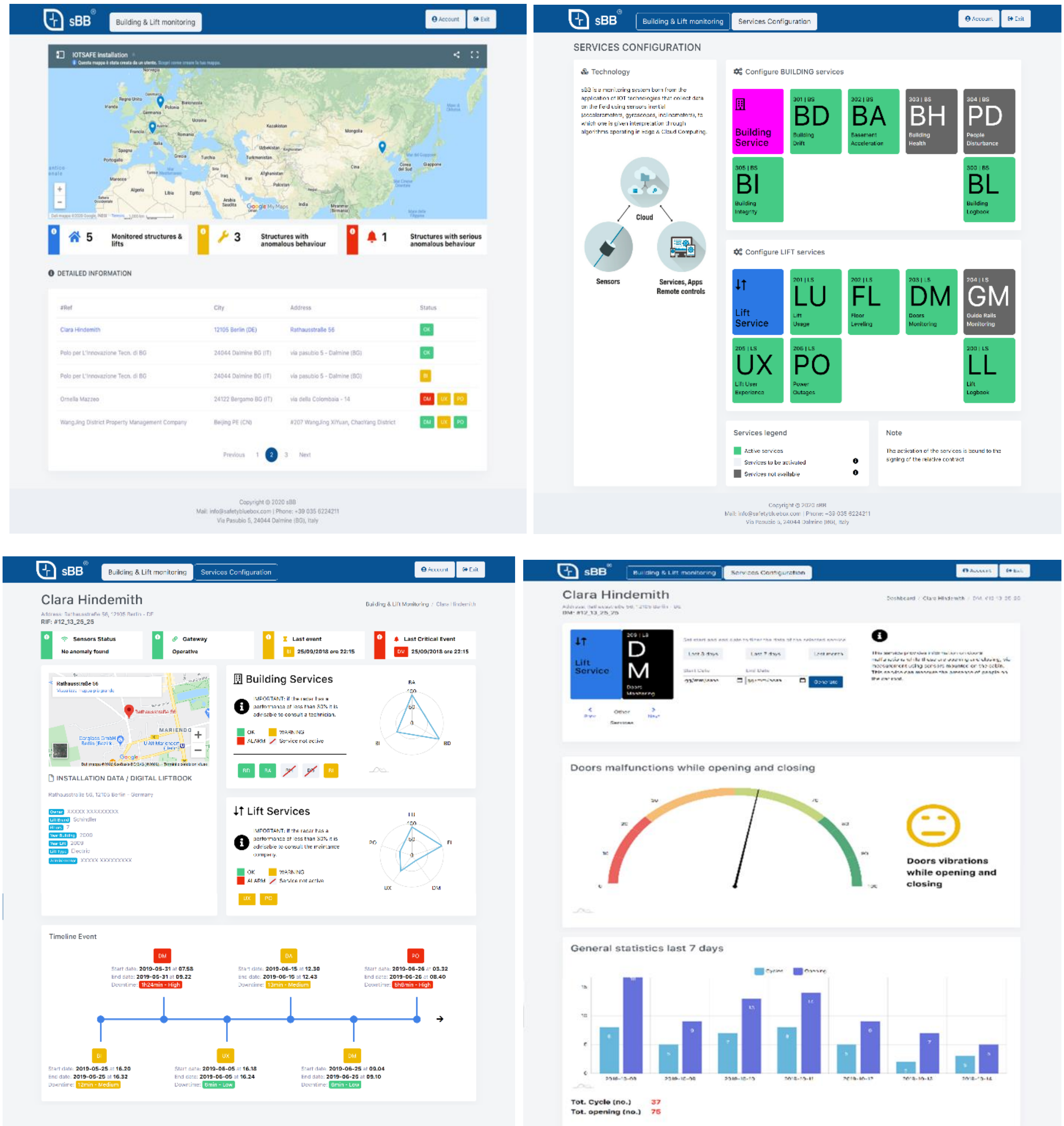

Figure 5 Typical monitoring platform

4 INSTALLATION

A proprietary technology design is installed in the lift shaft of a building. With the lift shaft rigidly connected to the building, any building movement (displacement, rotations, accelerations) is kinematically related to the shaft's movements; hence the same sensors installed to assess lift performance can provide the data needed to assess the structural stability of a building. Sensors are in key locations of the lift shaft, as illustrated in Figure 6.

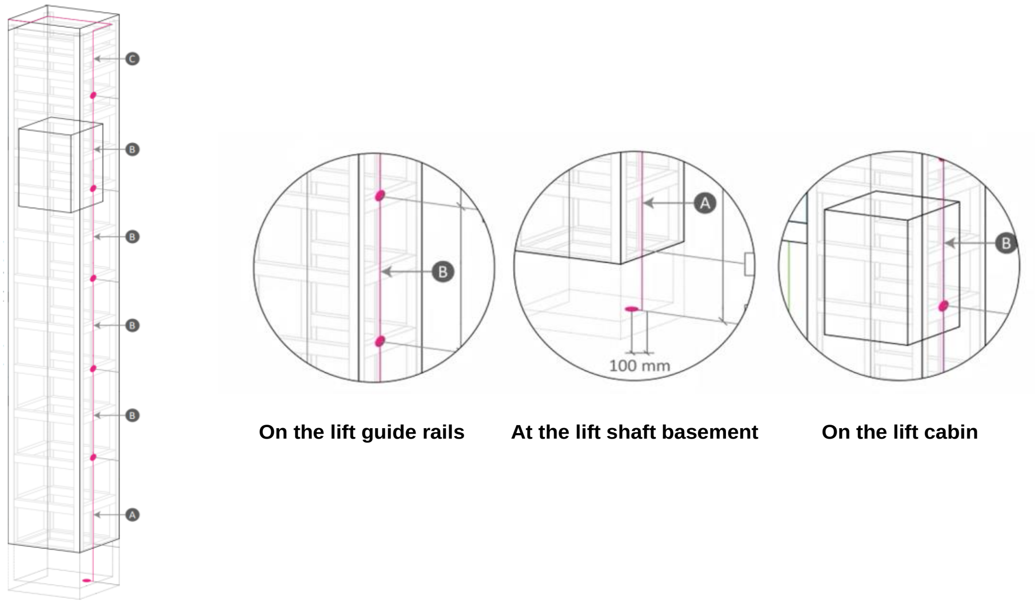

Figure 6 Typical sensors positioning

5 FEATURES / USE CASES

- **LIFT AND BUILDING LOGBOOK**: Can provide periodic reports or real-time notifications available on PCs and/or smartphones. The data supplied provide objective evidence of the presence of elements of disturbance or risk, together with valuable information which can be used to perform extraordinary maintenance works. Tracks the history of the lift and building performance response when subject to environment induced deformations and vibrations. A real black box that can also facilitate and accelerate the verification of post-event usability.
  - **LIFT USER EXPERIENCE**: By merging data resulting from different sensor measurements, it is possible to evaluate the exceeding of a set threshold, in accordance with a defined set quality of service.
  - **LIFT USAGE**: Provides a first-level statistical analysis of Lift Travel Data, measures the number of trips made, provides the count of major destinations, the mean travelling time, measures the capacity utilization over time and measures the total trip's distance on a monthly basis. Provides an estimation of the usage of the lift system for re-planning of basic maintenance services (e.g., lubrication). The lift usage analysis can be of support to a people traffic management analysis and for checking when the lift goes in a "out of order" mode.
  - **PEOPLE DISTURBANCE**: Measures vibrations in the three axial dimensions, even those produced by the human activity (operation of industrial machines, road and traffic in general, building sites activity), and is used as an "indicator for potential disturbance to people".
  - **BASEMENT ACCELERATION**: Monitors the effects of earthquakes and nearby natural or human-induced vibrations (e.g., by subways) to the building basement. Motions that typically propagate in the ground.
  - **BUILDING DRIFT**: Computes the maximum and residual inclination of a building generated by external agents inducing oscillations. By analysing the data received from sensors, it is possible to assess the risks associated with a potential structural failure.
  - **BUILDING HEALTH**: Checks the structural response of a building to internal or external events. Detects the anomalies of the typical behaviour of a single building in its own

environment of reference in case of explosions, seismic swarms or building works in the vicinity, constantly monitoring the stability conditions thereof. A specifically designed algorithm can perform a dynamical identification of the building characteristic response, in terms of proper frequencies of vibration and damping properties.

- **BUILDING INTEGRITY:** The triaxial accelerometers of the sensors detect vibrations that can induce cosmetic damage to the building such as cracks, fissures and plaster detachments. In this way, the non-structural damage threshold is monitored.

6 KEY CHARACTERISTICS AND CAPABILITIES

Key characteristics of the solution include:

- Suitable for all lifts, both new and old. It is a system that guarantees maximum compatibility with the lift technology used (electric, hydraulic, legacy or newer)
- Key performance parameters of the lift (e.g. vibration, loading, speed/acceleration, friction, usage and working hours) are accurately measured via a kit of sensors strategically positioned.
- Valuable information on the structural behavior of the building can be obtained from the sensors installed in the lift shaft and used to detect structural behaviors.
- Real-time monitoring is continuously available to technicians and operators through a Cloud-based platform and dedicated app (PC, laptop, mobile phone); alarms can be sent to notify risks or failure.

With a bespoke predictive algorithm, it is possible to:

- Avoid unexpected breakdowns by sending an alarm when anomalies are detected
- Reduce lift downtime by enabling quick, remote diagnosis of failures
- Reduce on-site maintenance visits: increased efficiency and effectiveness, reduced costs
- Assess the wearing of components, manage preventive maintenance and spare parts stock optimization
- Increase safety overall of both lift and building
- Increase quality of service

7 SUMMARY

This paper has shown how it is possible to turn every lift into a monitoring tool for the structural health of buildings without impacting the privacy rights of individuals - aiming to ensure a high level of human health protection. The innovation brought is intended to impact our society; especially in a highly human-dense environment like communities, companies, and institutions. Typical users are the lift local and multinational companies as, through them, over 2 billion people use lifts every day on a worldwide scale. The innovation benefits also flat owners and tenants, building managers, lift maintenance companies, large owners (multinationals, hotel and commercial chains, banks, insurance companies, public administration owning building stock), facility managers, and civil protection institutions. The innovation will impact the entire AEC (Architecture, Engineering, and Construction) sector, insurance companies, lift manufacturers, and system integrators.

Lift manufacturers could adopt a new system to increase the safety of users in areas prone to risks of natural events or strong urbanization and differentiate their offer in the market. Owners with better awareness of the state of health of their assets will be able to protect their investments, reducing expenses. Public institutions will access data on the effects of natural events useful to coordinate rescue interventions and assessing buildings and lifts' "fit for use" status. Lift maintenance companies will monitor their lift fleets, optimizing their work by offering better service, avoiding non-productive or decisive exits and interventions, useless or providing too early replacements of components. Facility managers get simplified management of heterogeneous real estate assets, optimizing performance and costs, raising the overall level of safety. All users of lifts and buildings equipped with such system will enjoy greater safety and better comfort.

Continuous remote monitoring of lifts is a rapidly emerging technology and certainly a requirement of the predictive maintenance market. A lift monitoring solution with built-in “building features” improves processes, increases efficiency, improves profitability, but most importantly, increases people's safety and accessibility. The statistics of human losses and economic damages are overall alarming, and global awareness of this factor is currently arising. Turn every lift into a tool for monitoring the structural health of buildings is a unique solution in the current market landscape.

REFERENCES

[1] UNI9614: 2017 Misura delle vibrazioni negli edifici e criteri di valutazione del disturbo

[2] ISO2631/1:1997 Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration — Part 1: General requirements

[3] UNI9916:2014 Criteri di misura e valutazione degli effetti delle vibrazioni sugli edifici

[4] ISO4866:2010 Mechanical vibration and shock — Vibration of fixed structures — Guidelines for the measurement of vibrations and evaluation of their effects on structures

[5] “MEMS” also written as micro-electro-mechanical systems (or microelectronic and microelectromechanical systems. https://en.wikipedia.org/wiki/Microelectromechanical_systems and https://www.cnr.it/en/focus/029-4/mems-micro-electro-mechanical-systems-for-wireless-architectures

[6] “FE” Finite element.

BIOGRAPHICAL DETAILS

Andrew Gorin - BSc Geography (dissertation: the effects of climate change on sub-glacial fluvial sediment flow), MSc Construction Management, MRICS Chartered Surveyor. Previously consultancy positions held at CBRE and Barclays Investment Bank, now director at Specialist Lift Services, a London-based lift contractor specialising in non-standard and bespoke lift design and installation. Recent projects include designing a compliant safety edge system for a lift with curved under-driven glass doors and a lift in a private residence with TV panels on all faces of the lift car, including the automatic sliding doors – both projects were awarded funding from the UK government via R&D grant payment. SLS maintain over 2000 units for a diverse range of bluechip and public sector clients, and have been working alongside IoTSafe s.r.l to verify, improve and industrialise the aforementioned technology. Andrew has been a member of the Lift and Escalator Industry Association (LEIA) Contracts Committee since 2015.

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Paolo Riva - full Professor of Structural Engineering at the Department of Engineering and Applied Sciences at the University of Bergamo, where, from 2009 to 2015 he served as Dean of Engineering. Amongst other courses, Prof. Riva teaches Seismic Design of RC structures and is publisher of over 250 papers on subjects such as nonlinear analysis of RC structures, seismic behavior of RC structures, precast concrete elements, connections for precast structures and seismic retrofitting of existing structures. During his career, Prof. Riva coordinated and collaborated to several research and design projects. Since March 2016 he is Member of CEN-TC229 ‘Precast Concrete Products’ and Liaison of CEN TC229 to CEN TC250-SC8 ‘Eurocode 8: Earthquake resistance design of structures. Since March 2017 he is Convenor of TG ‘Cladding and Infill Panels’ of CEN TC250-SC8.

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Lift IoT: Turning Sensor Data into Value

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Keywords: IoT (Internet of Things), Data driven lift maintenance.

Abstract. When companies talk about IoT – the "Internet of Things", which typically refers to a system or device with sensors, a network for transmitting data, and a system that can process and trigger actions, it is today far more than just an industry buzzword. IoT is a critical part of turning data into value that can lead to improvement in operational efficiencies, reduced maintenance costs, and even real-time system adaptations for improved system performance. Most importantly, data is at the heart of any IoT product.

1 INTRODUCTION

In today's lift systems, there are already plenty of sensors installed for various functions, however, the full potential of the data out of these sensors is by far not yet exploited. Sensor data can be turned into useful information for lift companies, as well as for real estate owners and facility managers. IoT and data-driven predictive maintenance can dramatically enhance the lift companies' efficiency. Real scenarios and the real benefits will be explored.

2 UNLOCKING THE POWER OF DATA IN LIFT SENSORS

Various sensing devices built into modern lift installations, from simple light curtains to complex time-of-flight sensors, are already capable of collecting a large amount of data. This section provides specific examples with corresponding data types that could be derived and integrated into an IoT solution.

2.1 Absolute positioning system and safety supervision

The combination of an absolute positioning system and the new generation of powerful EN 81-20/50-compliant safety supervision unit is capable of providing a large amount of valuable data. The car position and velocity are being continuously monitored. At any moment, it is known whether the car is travelling or stationary. Of course, the exact car position in [mm] in the shaft is known; from it, the car's speed [m/s] and acceleration [m/s^2] can be easily calculated. Furthermore, the configuration of the lift can be extrapolated, providing information on the number of floors and the distance between them [see Fig. 1].

More interestingly still, statistical usage data can be derived, including:

- total trip counter,
- number of trips per floor,
- total travelled distance.

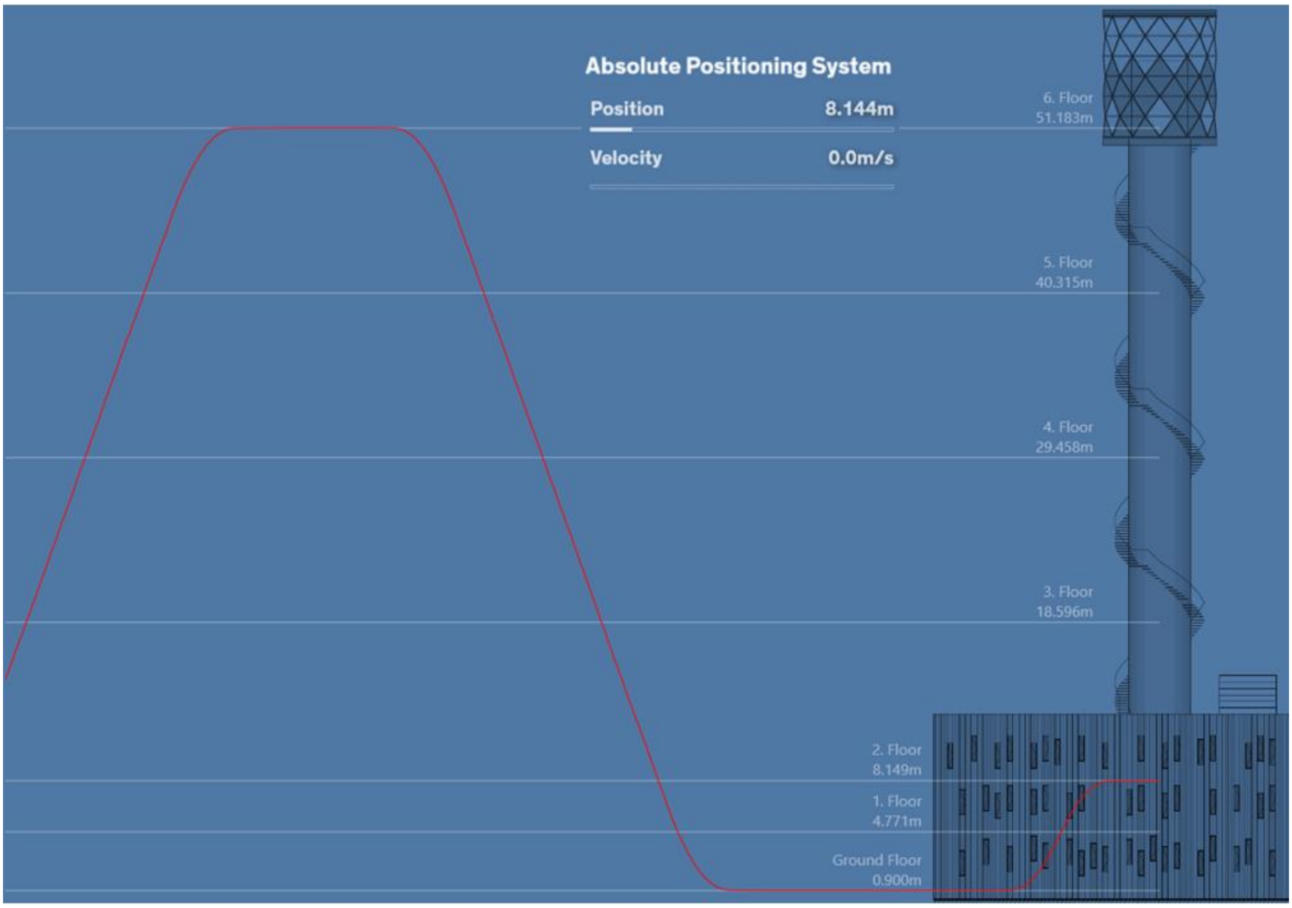

Figure 1 Current lift position, velocity and trip pattern in a six-floor tower

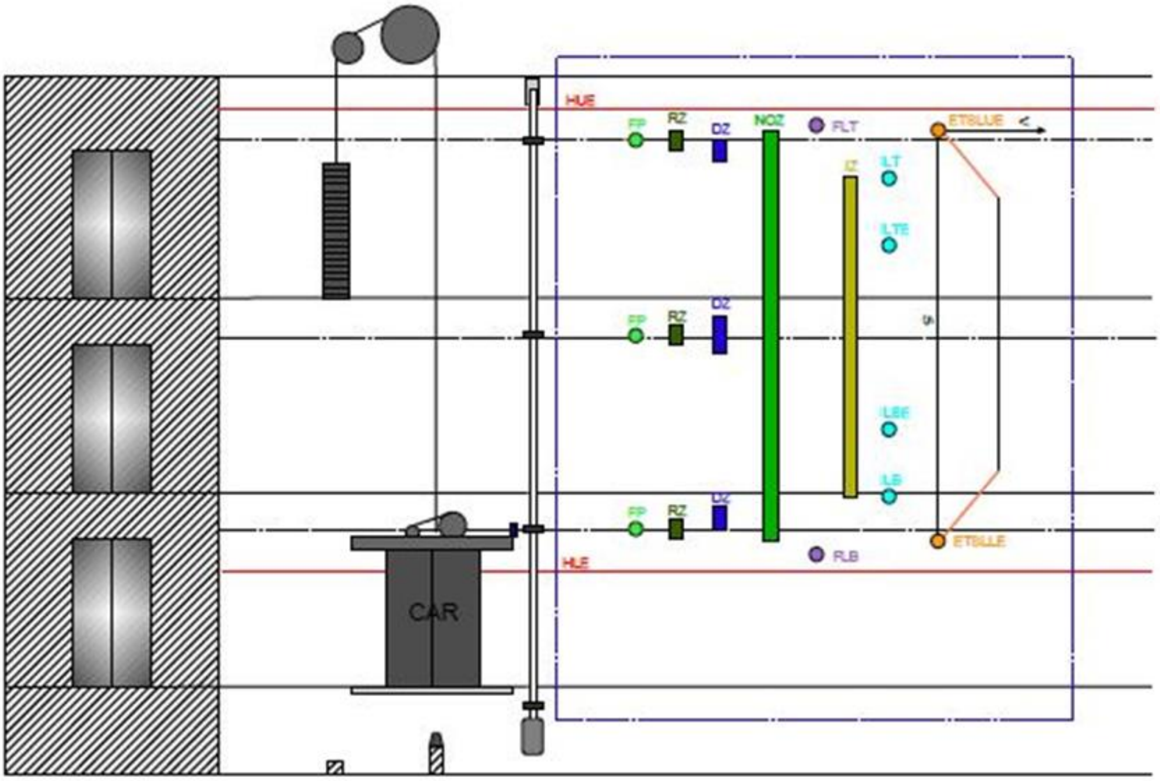

Figure 2 Shaft definition of a 3-floor lift representing different car position zones

The safety supervision unit monitors several additional data points pertaining to the car position [Fig. 2] and the lift status, as listed below and visualized in Fig. 3.

Car position:

- leveling, re-leveling zone
- final limit switches (ON/OFF)
- inspection limit switches (ON/OFF)
- extended inspection limit switches (ON/OFF)

Door:

- door status (OPEN / CLOSE)
- door contacts monitoring (faulty / bridged)

Safety:

- Safety chain status (OPEN / CLOSE)
- Overspeed detection
- Detection of unintended car movement (UCM)
- Safety gear monitoring status (ON/OFF)

Other:

- Car inspection operation status (ON/OFF)
- Pit inspection operation status (ON/OFF)
- Car door roof status (OPEN / CLOSE)
- Pit door status (OPEN / CLOSE)

Figure 3 Current lift position, velocity, trip pattern, incl. trip status [travelling upwards] and additional status information of a 3-floor lift

2.2 Door safety edge device

The 2019 North American Elevator Safety Code (ANSI A17.1-2019 / CSA B44-19) defines new requirements for the means of detecting persons or objects between the doors (2D) or approaching the elevator (3D). A 2D light curtain combined with a 3D TOF sensor and a controller can fulfil all these code requirements [Fig. 4 and 5].

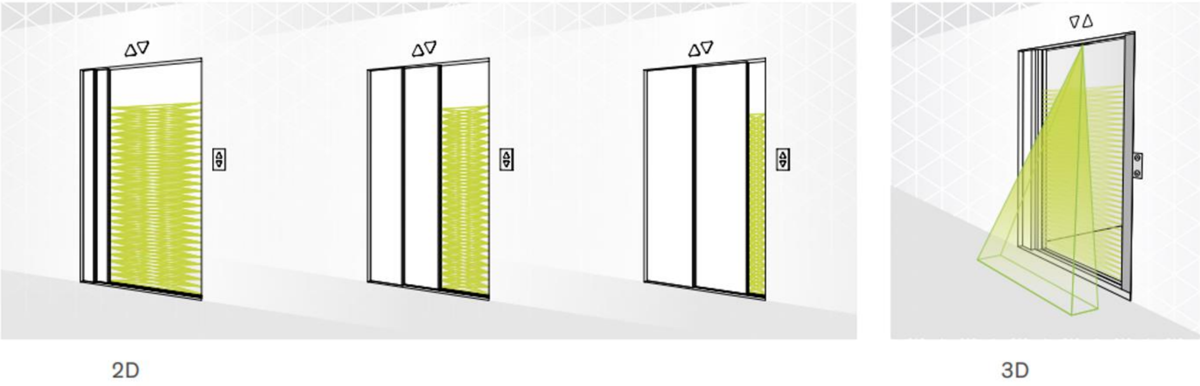

Figure 4 2D light curtain combined with a 3D ToF sensor

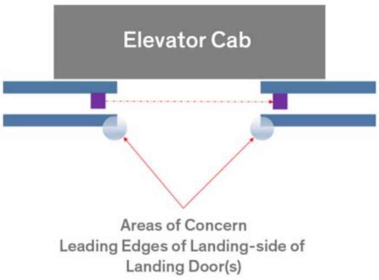

Figure 5 The detection areas of the system elements represented by red lines

Even a standalone light curtain collects valuable data that can be unlocked, such as the information that an object or person has been detected between the lift doors, as well as the number of such occurrences, i.e. counting people and objects leaving or entering the car. By combining it with a 3D sensor, further useful datasets can be derived.

People or objects in front of the cabin can be detected using ToF sensor technology. The technology makes it possible to distinguish between an object and a person, and to determine whether they are moving or stationary [Fig. 6].

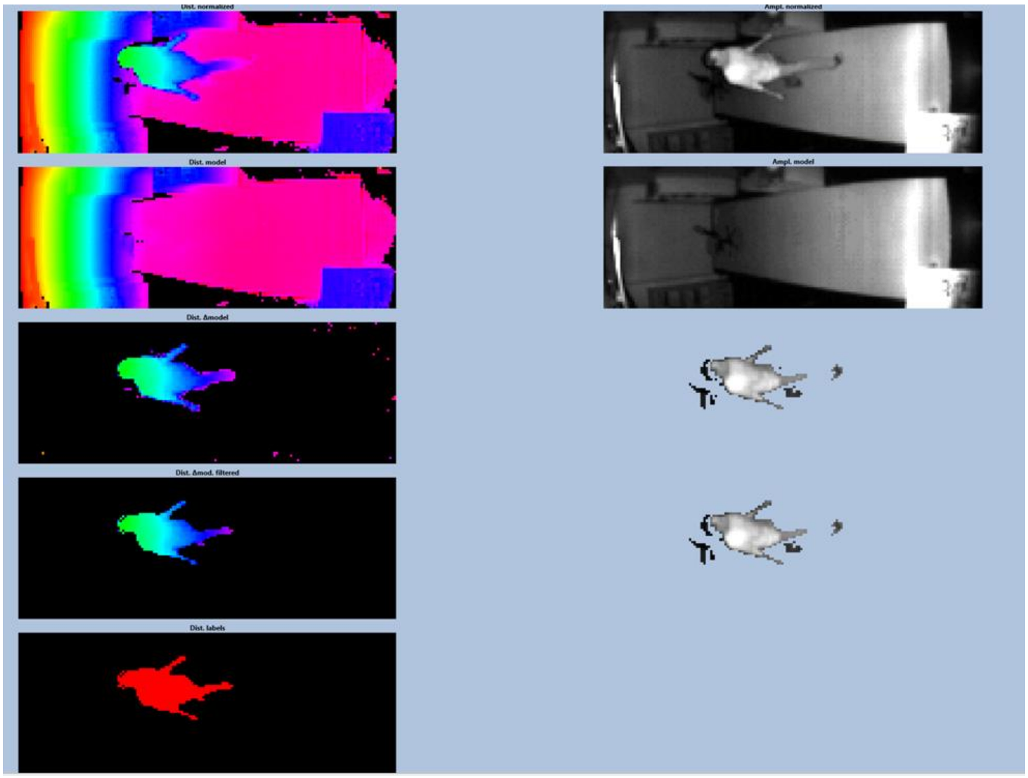

Figure 6 People or object detection using ToF and image processing technology

Not only the lobby area, but also the door itself can be monitored with ToF sensor technology and visualized as a greyscale image or an image providing distance information [Fig. 7].

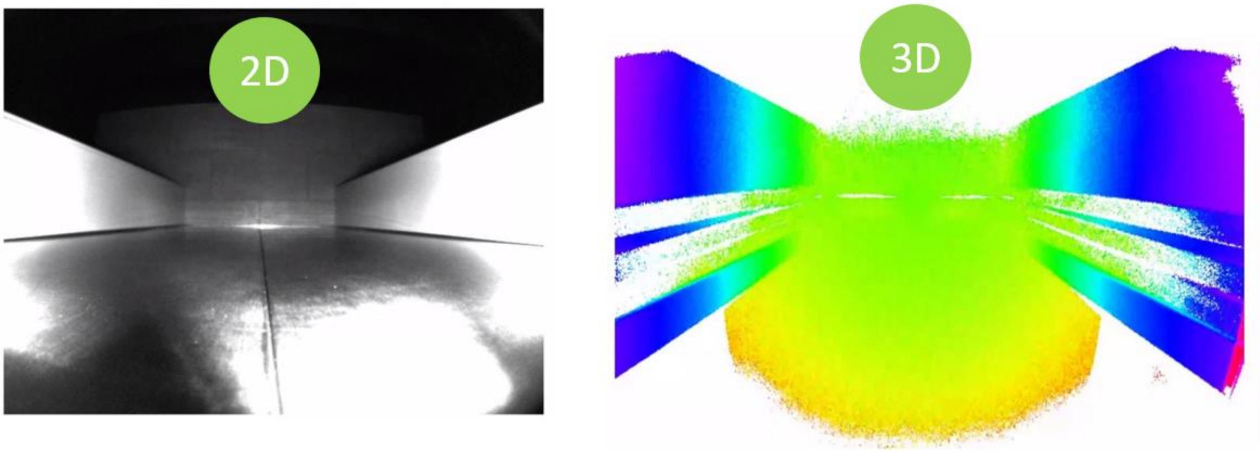

Figure 7 2D and 3D images of the door, the right one providing distance information

From this system, statistical usage data could be derived [as shown in the example dashboard in Fig. 8], including:

- Number of people and objects detected in front of the open doors and between the doors
- Door status (OPEN / CLOSE)
- Number of door cycles
- Number of door reversing
- Door opening and closing time

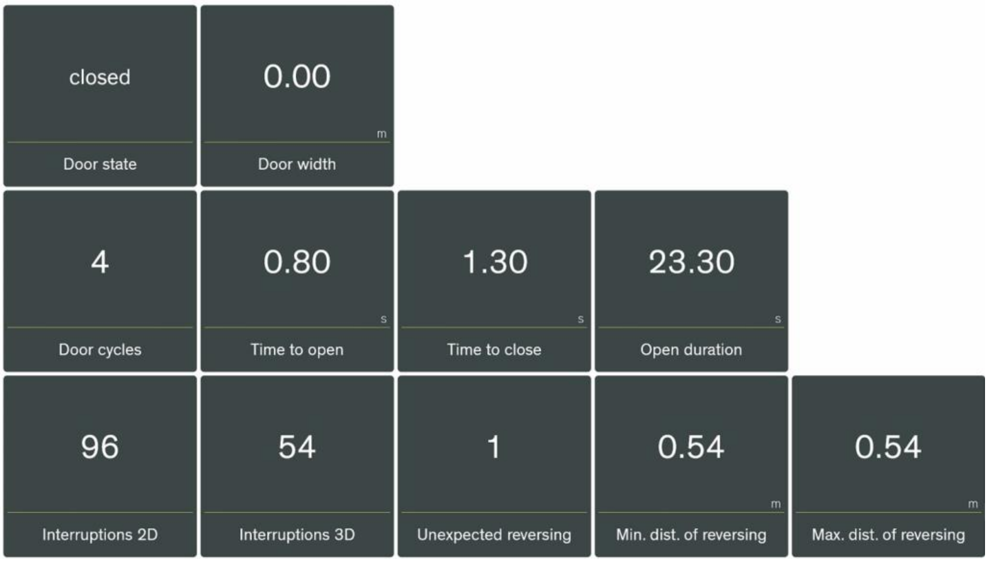

Figure 8 Example of a door statistic dashboard

3 IOT BENEFITS FOR LIFT COMPANIES AND THEIR CUSTOMERS

Inefficient maintenance processes, lack of data transparency, a large variety of lift types managed within one portfolio – the lift companies and their customers face a number of challenges in today's highly competitive lift aftermarket. IoT-enabled sensor solutions provide an answer to those challenges, paving the way towards data-driven maintenance.

3.1 Lift companies

The current maintenance model is time-based and consists of periodical checks at pre-defined intervals, as well as ad hoc repairs in case of breakdowns. It often happens that a single visit is not enough to eliminate a failure, due to scarce information on the possible root cause, lack of appropriate tools, spare parts, or trained personnel on site. Although going away from this traditional model is not yet in sight, access to relevant data would allow us to optimize it in a significant way.

Thanks to 24/7 condition monitoring and traffic analysis, it is possible to adapt the intervals between maintenance visits to the lift's actual wear and tear. Instead of working through fixed maintenance checklists, the lift company can put focus on repairs that are actually needed. More importantly, early detection of anomalies helps prevent complete breakdowns and thus reduce the number of unplanned maintenance visits in the long term. Based on root cause diagnostics, technicians are able to find and eliminate the error much faster, significantly reducing lift downtime. Based on data visualized in dashboards, the right team equipped with the right tools and the right parts can be allocated to a particular lift, and the visits can be prioritized based on failure severity. The same tool could also integrate troubleshooting instructions, allowing technicians to work in an even more efficient manner. It would mean a step away from reactive and towards proactive, predictive maintenance.

Another important benefit at hand is the possibility to collect data from all the installations in a portfolio, regardless of the lift types or models. IoT-enabled devices are easy to install in any type of lift and thus offer big advantages in simple modernization applications – connectivity is not limited to new installations. An overview of all lifts can then be visualized in a shareable dashboard, instantly showing warnings and red flags where anomalies or serious failures have been detected [Fig. 9]. This information can be accessed from any connected device and made available to all the interested parties, such as facility managers, building owners or even end users.

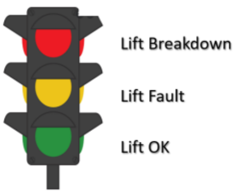

Figure 9 Lift status

Considering all the above, IoT solutions provide lift companies with a competitive edge in the increasingly connected and digitalized world and are becoming an important factor in driving business value. More and more companies are shifting from a product-first approach and reinventing their business models based on real-time data and connectivity [1, 2]. Access to data and increased maintenance efficiency constitute major added value for customers and foster their willingness to pay for a superior service experience. With the IoT in the lift market estimated to be worth $2Bn by 2028 [3], jumping on the IoT train can provide new sources of income and boost profitability.

3.2 Building owners and facility managers

The crucial change brought about by an IoT solution is data transparency. Lift companies can not only monitor the condition of their installations in real time, but also make this information available to relevant stakeholders. Visualized in shareable dashboards, the lift data becomes the basis for informed decisions and an important element of smart building ecosystems. As an example, people-counting and traffic analysis can contribute to better people flow management and to increasing the overall energy efficiency of a building.

Obviously, facility managers and building owners benefit from enhanced maintenance efficiency. Fewer faults and faster repairs result in reduced maintenance costs and higher lift availability, which in turn leads to higher satisfaction of the tenants and visitors. While the comfort of passengers is an important aspect, increasing passenger safety is the ultimate benefit of IoT-enabled sensor solutions - automatic notifications about a blocked lift with people trapped inside being just one example.

4 CONCLUSION

As illustrated by the examples of absolute positioning systems, safety supervisor units, time-of-flight sensors, and even light curtains, many elements of modern lift installations are already capable of collecting valuable data. IoT technology, in combination with machine learning and autonomous decision-making technologies, provide the key to unlocking the existing potential, bringing essential benefits to lift companies as well as their customers.

Although there are currently various types of IoT solutions for industrial use, the convergence of these multiple technologies, including sensors, connectivity, increasingly powerful embedded systems, and machine learning, is still ongoing. A challenge for the implementation of these IoT systems is the technological fragmentation.

REFERENCES

[1] L. Bernardi, S.E. Sarma and K. Traub, *The Inversion Factor: How to Thrive in the IoT Economy*, MIT Press (2017).

[2] G. Westerman, D. Bonnet and A. McAfee, *Leading Digital: Turning Technology into Business Transformation*, Harvard Business Review Press (2014).

[3] *IoT in Elevators Market Forecast to 2028 - COVID-19 Impact and Global Analysis By Component (Hardware, Software, and Services), Application (Preventive Maintenance, Remote Monitoring, Fault Diagnosis and Prediction, Advanced Reporting, and Connectivity Management) and End-User (Residential, Commercial, and Industrial)*, The Insight Partners, New York (2022).

BIOGRAPHICAL DETAILS

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Disinfection Efficacy Analysis of an Ultraviolet-C (UVC) Device for Escalator Handrails

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Keywords: Ultraviolet-C (UVC), Disinfection efficacy, Continuous and pulsed test, Escalator Handrails, Viruses and bacteria.

Abstract. The global Coronavirus pandemic is of urgent concern with its high transmission rate and rapid spread throughout the world from 2019. This paper introduces an Ultraviolet-C (UVC) device to be fitted on escalators which was designed to inactivate bacteria and viruses on the surfaces of handrails during escalator operation. Through a combination method of measurement and finite element analysis (FEA) simulation, the authors accurately calculated the UVC intensity, dosage, and distribution of the UVC device on a surface. The authors also describe how the UVC device works and detail the disinfection efficacy of the device to inactivate bacteria and viruses. In this work, efficacy of the device against two bacteria (E. Coli and S. Aureus) and two corona viruses (HCoV-229E and HCoV-OC43) were tested. All tests were conducted in two modes of the UVC device: continuous mode and pulsed cyclic mode. Based on the test results and combining UVC parameters, the disinfection efficacy of the UVC device was analysed. The investigation found, i) the relationship between the disinfection efficacy and the UVC parameters of the device, ii) the relationship between the disinfection efficacies of continuous and pulsed test mode and iii) the dosage for killing 99% pathogens (D_{99}) of the UVC device for the two bacteria and viruses based on escalator operation.

1 INTRODUCTION

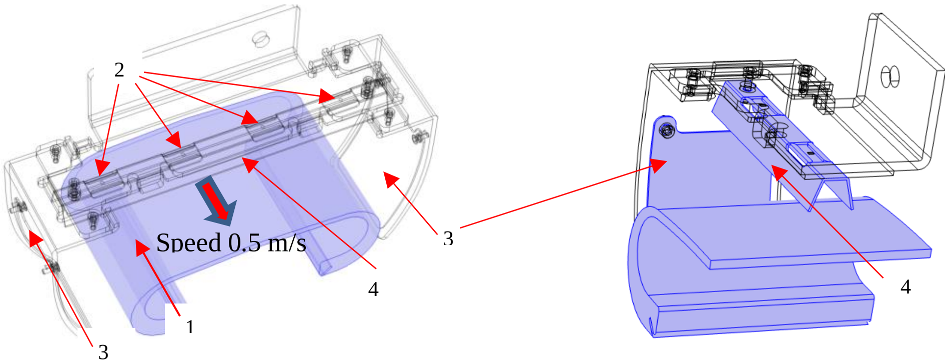
The COVID-19 pandemic brought the importance of available and reusable Personal Protective Equipment (PPE) into sharp relief. As requirements for clean, hygienic spaces become more critical to our health and wellbeing, UV devices provide a proven and effective means of disinfecting public and shared spaces. Studies show that bacteria, mold and fungi can be killed, and viruses can be inactivated by UVC [1-3]. UVC energy photochemically interacts with the RNA and DNA molecules in a virus or bacteria to render these microorganisms non-infectious [1- 4].

The efficacy of UVC with wavelengths of 222 and 254 nm has been analyzed in many studies. But some researches also pointed out: the reality is that 254 nm is not the peak absorption wavelength of bacteria and viruses but is simply a convenient wavelength for mercury lamps. In fact, the peak absorption wavelength of bacteria and viruses is around 265 nm. More efficient and compact UVC light emitting diodes (LEDs) have a peak wavelength between 275 nm and 280 nm and are just as effective as 254 nm for purification purposes. Short wavelength UVC, of 250–280 nm, is considered the most lethal of wavelengths due to its capability of inactivating microorganisms as it gets strongly absorbed in their nucleic acids. This often leads to the formation of cyclobutene pyrimidine dimers (CPD) in the nucleic acid strands, which might cause defects in cell replication and eventual cell death [5, 6].

The UVC disinfection efficacy is related to the dose of UVC on a surface (or in a space) [1]. Although the UVC may not be powerful enough (intensity) for large spaces and areas, it can be controlled to provide very high intensity on a small spaces or areas to create a high disinfection efficacy for bacteria and viruses.

Draka EHC is the largest escalator handrail manufacturer in the world and these are widely used in public places. From the beginning of the COVID-19 pandemic, Draka EHC cooperated with IRtronix

Inc. to develop a UVC device for cleaning the surface of escalator handrails. The UVC device is mounted inside the escalator system, so it is not visible or exposed to people using the escalator. Please see Figure 1, it shows the structure of the UVC device and position relationship between the UVC device (transparent part) and an escalator handrail cover in service. The UVC device mainly consists of a frame, 4 UVC LEDs, 2 side reflectors and a top reflector. Table 1 shows the main parameters of UVC LEDs.



1. Handrail, 2. UVC WICOP LED, 3. Side reflectors, 4. Top reflector, 5. Frame

Figure 1 The UVC device and a piece of handrail

Table 1 Electro-Optical Characteristis at 150mA (T$_a$=25º, RH=30%)

Parameter	Symbol	Value	Unit
Peak Wavelength	λ_p	275	nm
Optical Output Power	Φ_e	11.5×4	mW
Forward Voltage	V_F	6.5	V
Spectrum Half Width	$\Delta\lambda$	11	nm
View Angle	$2\Theta_{1/2}$	135	deg.

To best understand the disinfection performance of this device it is necessary to know the UVC dose that will be delivered to the surface of an escalator handrail and the effect of this dose on pathogens. To determine the dose delivered the UVC device was analyzed by combining UVC measurement (calibration) and FEA simulation; and further the relationship between the UVC intensity and dose with the setting parameters of the UVC device and handrail was obtained. To determine the disinfection efficacy of this device, Draka EHC collaborated with the University of Toronto (UofT) department of Materials Science and Engineering. The UofT team tested the device against two bacteria (E. Coli and S. Aureus) and two corona viruses (HCoV-229E and HCoV-OC43) under different conditions. Based on the test results we were able to determine; i) the relationship between the disinfection efficacies of continuous and pulsed cyclic test modes and ii) the D_{99} (99% dosage) of the UVC device for the two bacteria and two viruses based on an escalator in normal operation.

2 THE UVC DEVICE AND FEA ANALYSIS

The UVC device will be installed inside the escalator. It creates a wide band of high intensity UVC on the handrail surface and scans the entire length as the escalator operates. The typical handrail running speed is 0.5 m/s and typical length is 30 m, so in around 60 seconds the handrail completes one cycle and the UVC device completes scanning the entire surface of the handrail.

A study has shown the disinfection efficacy of UVC is proportional to the UVC dose [1]. How to scientifically measure the dose on the handrail surface is essential to evaluate the disinfection efficacy of the UVC device. To analyze the UVC intensity and dose delivered to the handrail surface, a combination of FEA simulation and experimental measurement was used. After building the relationship between the simulation values and real UVC values, the FEA simulation was used to calculate the UVC intensity, dose, and distribution for the handrail surface.

Ray Optics Module of COMSOL Multiphysics [7] was used to simulate UVC in this paper. Figure 2 shows the calibration procedure for UVC device intensity and how to build a relationship between the simulated result and measured result. The UVC intensity, dose, and distribution are not specified by the manufacturer and the actual values were measured. Then, based on the parameters of the measurement, COMSOL was used to simulate the UVC intensity and dose. Finally, by comparing both measured and simulated results the relationship was developed.

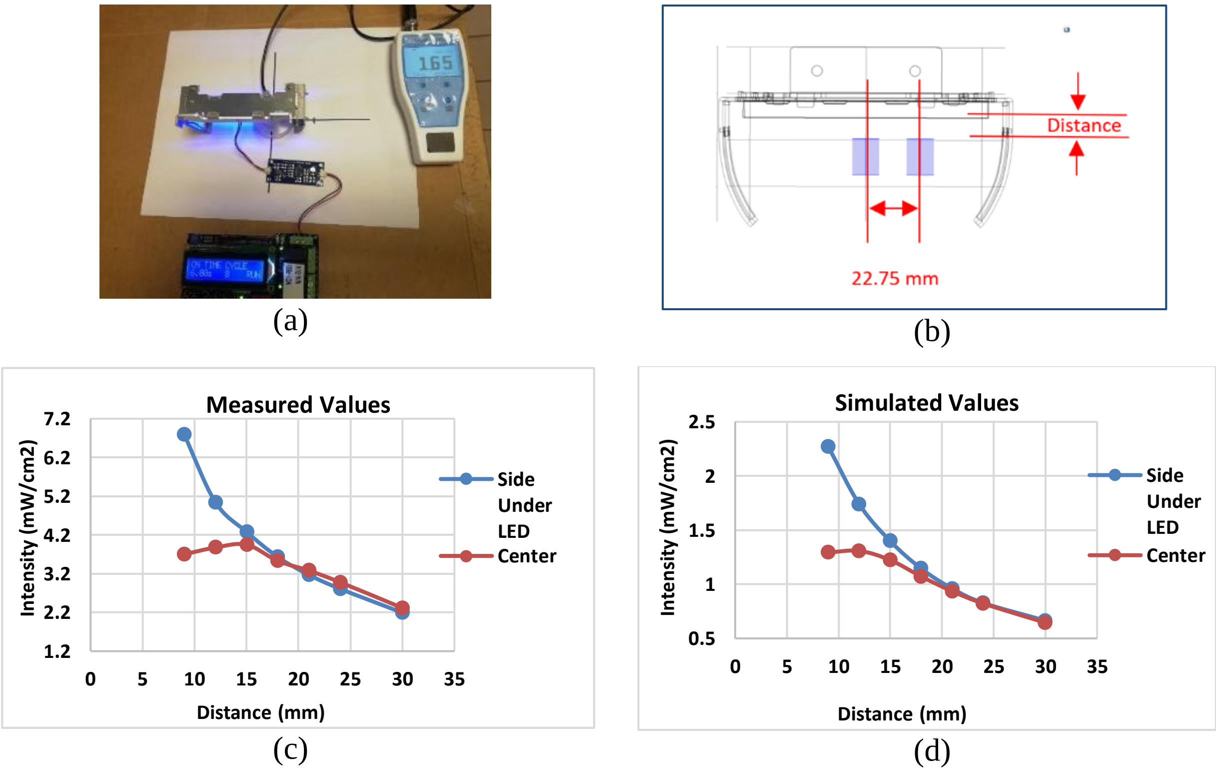


Figure 2 The calibration of the simulation results for UVC device

In Figure 2 (a), a commercial UV meter (ILT770-UV meter, International Light Technology) was used to measure the intensities of the UVC device. The sensor of UV meter has a round sensor with area 1 cm^2. The meter was used in two positions to measure the intensity of the UVC device. The first position was located exactly under the center of the UVC device (called center) and the second position was located either right or left side of center (called side) (See in Figure 2 (b)). The distance between the center and side positions was 22.75 mm. In Figure 2 (c), the measured intensities of these two positions with various distances (8, 12, 15, 18, 21, 24 and 30 mm) between the edge of the top reflector to sensor surface of the UVC meter are shown. In Figure 2 (d), the intensities of two positions with the exact distances used during the measurement in Figure 2 (a) were simulated. By comparing these two results it was found that they have a very similar shape and trend. That means the simulated FEA result well described the UVC physics. However, the absolute values are different between the measured and simulated results. Through linear regression method, the following relationship between the measured and simulated values were easily obtained:

$$\frac{\text{Real intensity}}{\text{Simulated intensity}} = 3.06$$

In this paper, all analysis of the UVC device such UVC intensity, dose, and distribution is based on FEA simulation results by using the correction parameter of 3.06.

In Figure 3, the simulated UVC intensity distribution on the handrail surface looks like a band shape. The band shape and dimension are mainly decided by the top reflector shape, dimension, and distance between the UVC device to the handrail surface. The top surface of the handrail is much closer to the UVC LEDs and the intensity is higher than on the two curved sides. Also, a higher intensity is shown in the center than on the two sides (Figure 3 (b)). The intensity decreases with increased distance between the UVC LEDs and handrail surface (Figure 3 (b)). At the same time, the UVC distribution band width is increased with distance.

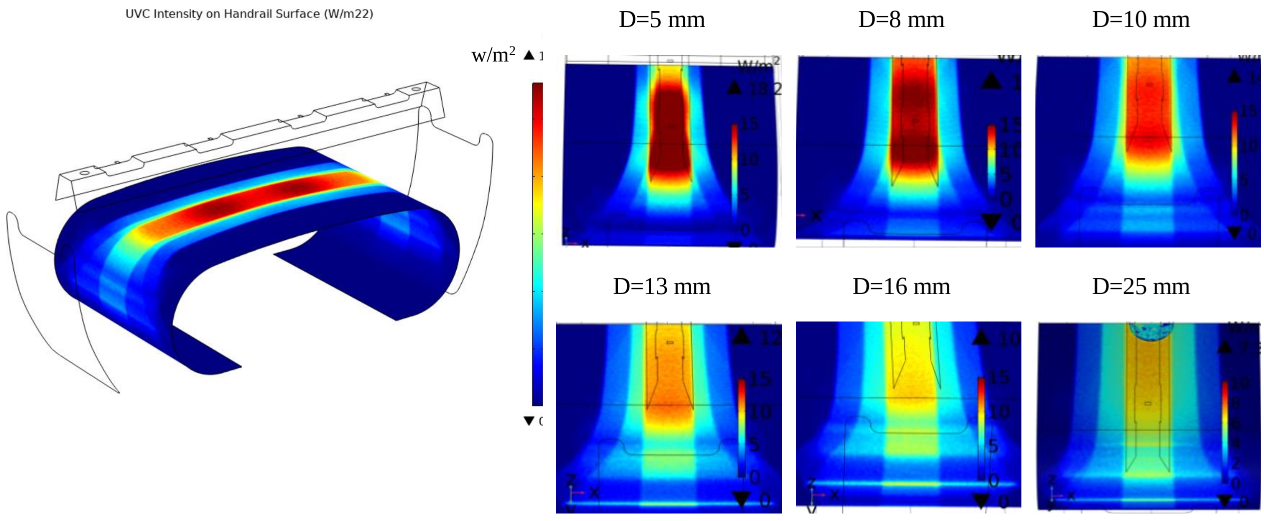
The dose delivered equals intensity multiplied by the exposure time. Based on the simulated intensity, the dose on the surface was easily calculated. However, because the intensity is not constant on distributed surface area, it is not easy to calculate the dose on the handrail surface because it is moving at a constant speed (0.5 m/s). Therefore, the dose received by the handrail surface is not even. In order to accurately calculate the dose on the handrail surface, several parallel lines (to mark the position on the handrail surface) were drawn (Figure 4). The dose received on each line is a constant. The following equation is used to calculate the dose along each line,

$$Dose = \int f(x,\, y)dt = \int f(x,\, y)\frac{dy}{v} = \frac{1}{v}\int f(x,\, y)dy$$

Where $f(x, y)$ is intensity at point (x, y), $\int f\ (x,\ y)dy$ is line integration (simulation easily provides this data for each line) along y axis (handrail travel direction). v is the handrail running speed.

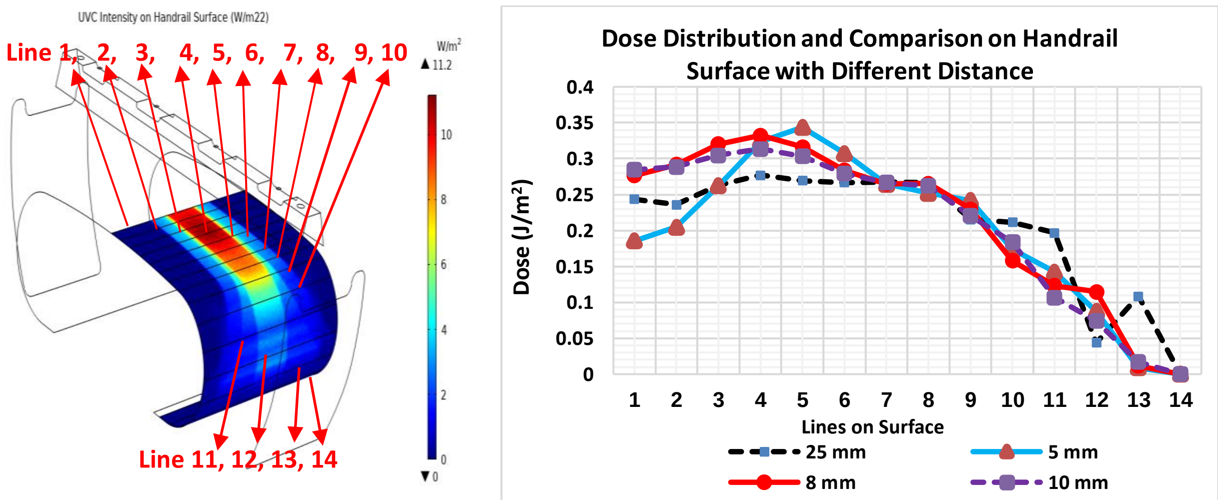
The intensity on each line was determined by using FEA simulation method. The UVC dose along each line with various distances between the device and handrail surface was calculated in one rotation of the handrail in service (in Figure 4 (b), only half was shown because of symmetrical shape). Obviously, the dose distribution on the surface varies with location and various distance. However, it seems to not be following any trend. The reason is although intensity is strong with closer distance, the width of distribution band area is narrower (Figure 3). The total integration may not be higher. On another side, the doses on two curved sides of the handrail is significantly lower than the top area despite of using side reflectors due to longer distance from the UVC LEDs. Based on this simulated result, the distance between the UVC device and handrail surface is less significant to the total dose received on handrail surface than originally suspected. A spacing of 8-10 mm is recommended as it provided the most balanced distribution on the handrail surface.

We have shown how the intensity and doses on the handrail surface were determined. To evaluate the disinfection efficacy of this UVC device, some pathogens needed to be tested using this UVC device. In this work, 2 bacteria and 2 viruses were chosen.



(a) (b)

Figure 3 The intensity distribution on handrail surfaces with various distances



(a) (b)

Figure 4 The calculated doses along each line on handrail surface

3 THE DISINFECTION EFFICACY TEST OF THE UVC DEVICE FOR PATHOGENS

In order to investigate how efficient the UVC device was at inactivating pathogens, Draka EHC collaborated with Professor Hatton’s team at UofT. The disinfection efficacy logarithm (Log) reduction or percentage reduction of the UVC device for pathogens was tested under two conditions: continuous exposure time and pulsed cyclic exposure time. The continuous mode test means the UVC device is on all the time during the test until the preset test time is reached. The test of continuous mode was used to determine the exposure time range required to achieve a log reduction of 1 or greater for the tested pathogens. In pulsed cyclic mode, testing the device works in pulses: on (ON) for 0.1 seconds then off (OFF) for 59.9 seconds to complete one cycle of 1 minute. This cycle repeats until the specified number of exposure cycles were reached. For the test of pulsed cyclic mode, the total setting test time is determined according to the test results of continuous mode. It equals the pulsed cyclic time (0.1s) multiplied by the number of cycles.

The pulsed cyclic test was designed to mimic the real condition during the running of the handrail on an escalator: the handrail surface receives a certain amount of UVC doses, which is not continuous. It is only exposed to UVC when it passes under the scanning band of the UVC device; after passing through that zone, there is a gap of almost 60 seconds (a loop cyclic time of a typical handrail is 60s) before the next UVC exposure. Also, by comparing these two test results (continuous mode and pulsed cyclic mode), it will show whether there was significant difference in disinfection efficacy between intermittent or continuous exposure.

For each pathogen, the test under continuous mode was first conducted to find the effective time range of the UVC device. Then, based on this result of the continuous mode, the test of pulsed cyclic mode was conducted to find the disinfection efficacy of the UVC device. The distance 8 mm between the edge of top reflector of the UVC device and test samples (surface) was used (real distance is 15 mm between LEDs to the test surface).

Two bacteria (E. coli and S. aureus) were tested using the setup in Figure 5 (a). The test samples were prepared using a square petri dish with a gird of thirty-six squares (6×6), each square with dimension 13×13 mm (Figure 5 (b)). Three pathogen droplets (10 uL each) were inoculated on the surfaces of a strip with size (1 cm×3.9 cm) (Figure 5 (c)). The strip (with 3 samples) was put on a flat surface (setup is shown in Figure 5 (a)).

Figure 5 (d) shows test setup for two seasonal corona viruses (HCoV-229E and HCoV-OC43). 50% Tissue Culture Infectious Dose (TCID50) assays are used to quantify virus titers.

If the setting distance between the UVC device and the pathogen sample surface is 8 mm, the simulated UVC distribution area on a surface is shown in Figure 5 (e). During the test, the test samples must be kept in the center red strip area (80×11 mm) and in this area the average UVC intensity equals 3.78 mW/m2. The UVC dose equals the UVC intensity multiplied by the exposure time for the continuous exposure mode or the pulsed cyclic mode. The total pulsed cyclic exposure time equals the exposure time of a cycle (i.e., 0.1s) times the total number of cycles.

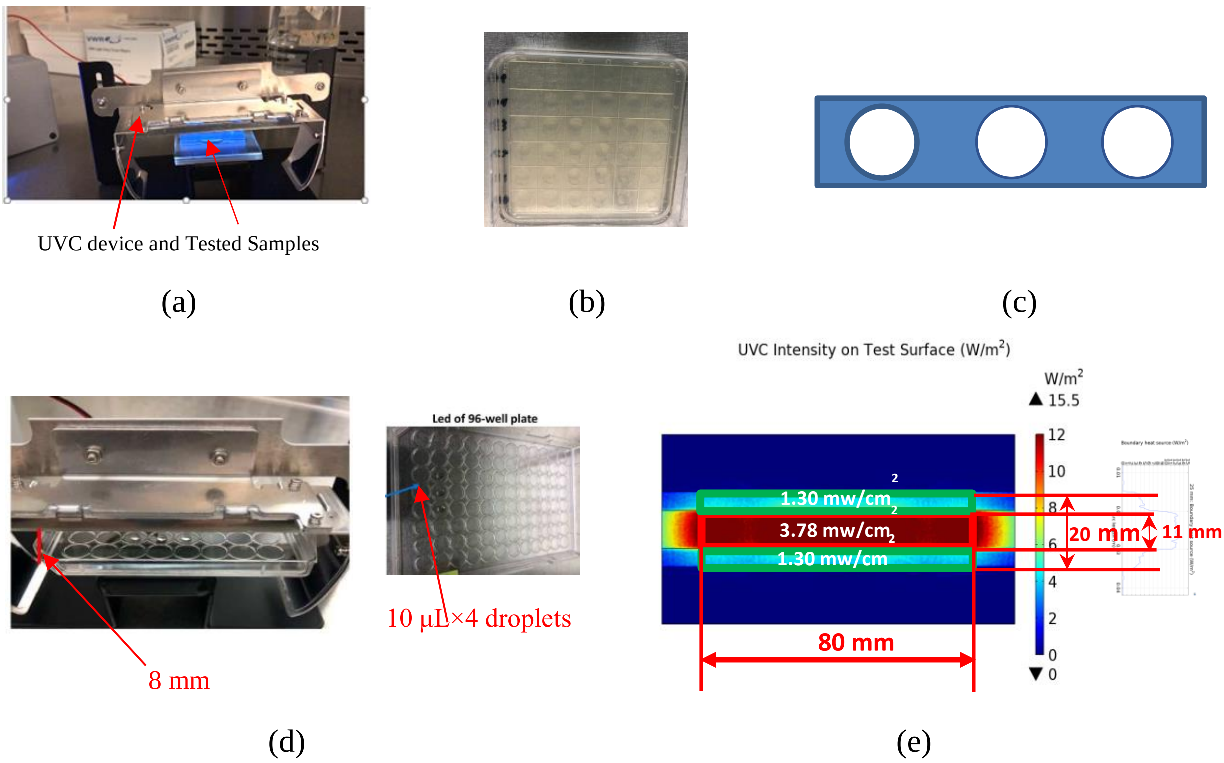


Figure 5 The test setup of sample positions and the UVC device

At the beginning of testing, 3 different exposure time durations were chosen for the continuous mode test based on some references in literature [8]. Then, based on the test results of the continuous mode, the 3 test time durations of the pulsed cyclic mode were chosen. In general, if the disinfection efficacy (measured as log reduction) obtained from the continuous mode test is in reasonable range (e.g., 1-4), the time of the pulsed cyclic exposure test will use the same "total" test time as the continuous mode test. Otherwise, an adjustment is needed. Figure 6 shows all tests conducted by the University of Toronto. It includes all information about the tests, pathogens, test times of continuous mode and test times of pulsed cyclic mode.

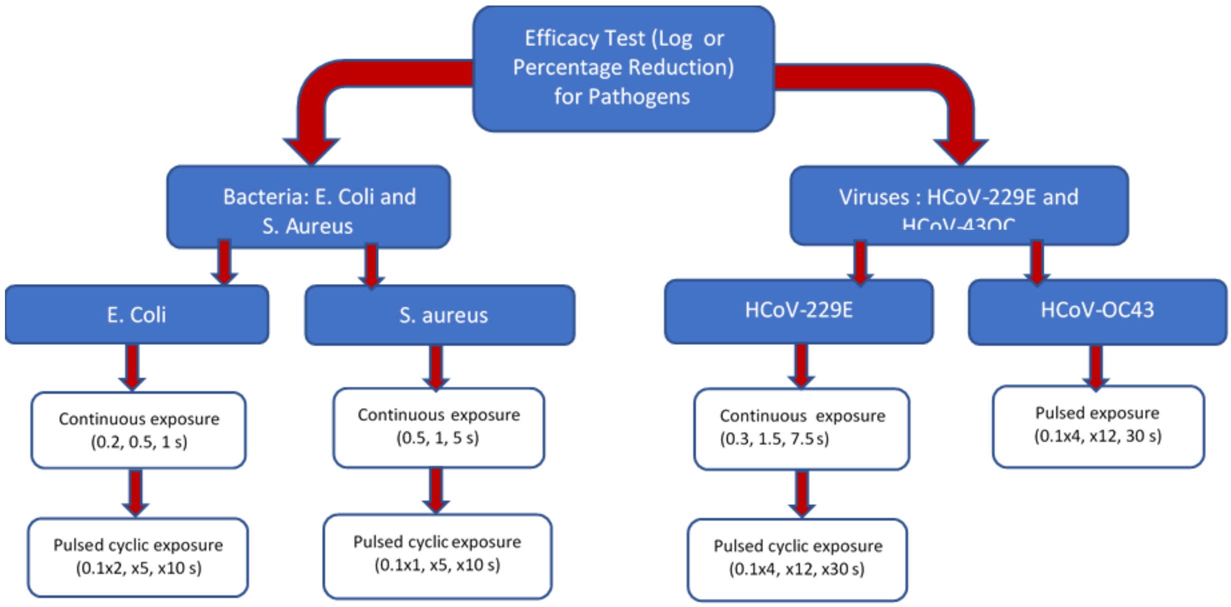


Figure 6 Efficacy Test of the UVC device for inactivation of pathogens

The disinfection efficacy of the UVC device is calculated by either percent reduction or logarithm (log) reduction. The calculation equations are:

$$Log\ Reduction = Log\ A/B$$

$$Percent\ Reduction = \frac{A-B}{A} \times 100\%$$

Where A is the number of viable pathogens before treatment; B is the number of viable pathogens after treatment.

Tables 2-5 show all the test results. Table 2 shows the test results for bacteria E. coli using continuous mode and pulsed cyclic mode. After completing the continuous mode test, the log reduction was very high. Based on this the total exposure times for the pulsed cyclic mode test were (0.1×1, 0.1×2 and 0.1×5 seconds), less than the times of the continuous mode test. The result was that the UVC device, with a 0.1 second exposure, could kill almost all E. coli bacteria (>99.8%).The UVC dose applied to the handrail surface in 0.1 seconds is; 3.78 $mW/cm^2 \times 0.1$ s= 0.378 mJ/cm^2.

Table 3 shows the test results for bacteria S. Aureus using continuous mode and pulsed cyclic mode. After completing the continuous mode test, the time range (0.5 to 5s) was considered too broad, so for pulsed cyclic mode test, a narrower time range was chosen of 0.1 - 1.0s. This showed that the UVC device, with an exposure time of 1.0 s, which provides a UVC dose of 3.78 $mW/cm^2 \times 1.0$ s= 3.78 mJ/cm^2, could kill almost all S. aureus bacteria (>99.87%).

Similarly, Table 4 shows the test results for corona virus HCoV-229E using continuous mode and pulsed cyclic mode. After completing the continuous exposure test, the time range (0.5 to 7.5 s) was broad, so for pulsed cyclic mode test, a narrower time range was chosen (0.4 - 3.0s). This showed that the UVC device, with 1.5 second exposure time, i.e., the dose=3.78 mW/cm^2×1.5 s= 5.67 mJ/cm^2, could kill almost all virus HCoV-229E (>99.3%).

Finally, Table 5 shows the test results for corona virus HCoV-OC43 using pulsed cyclic mode. The time range was chosen based on the test results of HCoV-229E continuous mode test. It shows that the UVC device, with 0.4 second exposure time, i.e., the dose=3.78 mW/cm^2×0.4 s= 1.512 mJ/cm^2, could kill almost all virus HCoV-OC43 (>99.3%).

Table 2 The test results for bacteria E. Coli

Continuous Exposure Test					Pulsed Cyclic Exposure Test				
Time (s)	Number of microbes (before treatment)	Number of microbes (after treatment)	% Reduction	LOG_{10} Reduction	Time (s)	Number of microbes (before treatment)	Number of microbes (after treatment)	% Reduction	LOG_{10} Reduction
0.2	3.2X10^5	74.3	99.977	3.63	0.1X1	1.93X10^4	26.3	99.864	2.87
0.5	3.2X10^5	19.33	99.994	4.22	0.1X2	1.93X10^4	18.3	99.905	3.02
1.0	3.2X10^5	0.67	99.9998	5.68	0.1X5	1.93X10^4	3	99.984	3.81

Table 3 The test results for bacteria S. aureus

Continuous Exposure Test					Pulsed Cyclic Exposure Test				
Time (s)	Number of microbes (before treatment)	Number of microbes (after treatment)	% Reduction	LOG_{10} Reduction	Time (s)	Number of microbes (before treatment)	Number of microbes (after treatment)	% Reduction	LOG_{10} Reduction
0.5	3.43x10^4	1.2x10^3	96.4	1.4	0.1x1	6.9X10^4	ND	ND	ND
1	3.43x10^7	3.5X10	99.999898	6.0	0.1X5	6.9X10^4	91	99.87	2.9
5	3.43x10^9	4.3	99.99999	8.9	0.1x10	6.9X10^4	6.3	99.99	4.0

Table 4 The test results for virus HCoV-229E

Continuous Exposure Test					Pulsed Cyclic Exposure Test				
Time (s)	Number of microbes (before treatment)	Number of microbes (after treatment)	% Reduction	LOG_{10} Reduction	Time (s)	Number of microbes (before treatment)	Number of microbes (after treatment)	% Reduction	LOG_{10} Reduction
0.3	9.28x10^5	1.36x10^5	85.3	0.8	0.1x4	1.36X10^6	1.36X10^5	90	1
1.5	9.28x10^5	6.3x10^3	99.3	2.2	0.1X12	1.36X10^6	2.0x10^3	98.85	2.8
7.5	9.28x10^5	9.3	99.999	5.0	0.1x30	1.36X10^6	9.3	99.9993	5.2

Table 5 The test result for virus HCoV-OC43

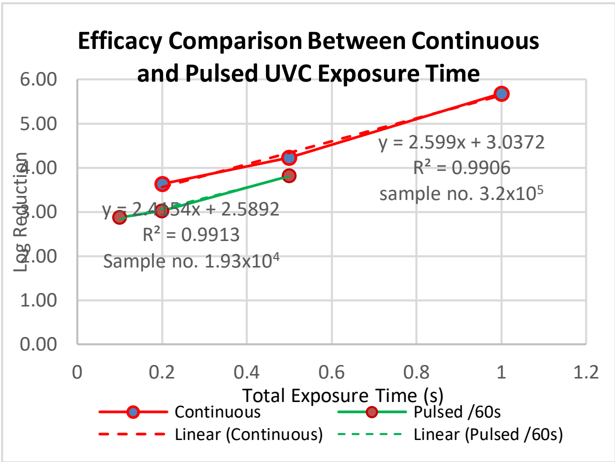
Pulsed Cyclic Exposure Test				
Time (s)	Number of microbes (before treatment)	Number of microbes (after treatment)	% Reduction	LOG_{10} Reduction
0.1x4	4.3X10^7	2.9X10^5	99.3	2.2
0.1X12	4.3X10^7	9.3X10^3	99.978	3.7
0.1x30	4.3X10^7	9.3	99.9998	6.7

4 THE RESULTS AND DISCUSSION

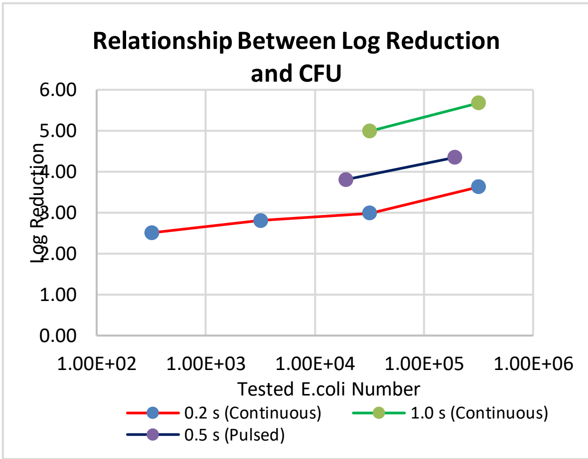
Using the experimental results provided above, we are able to examine the relationship between pulsed and cyclic exposure on the tested pathogens.

The test for bacteria E. coli was designed to compare the disinfection efficacy for both continuous and pulsed modes. The log reduction with exposure time for both modes is shown in Figure 7 (a). The red line represents the continuous result and green line represents the pulsed cyclic result. The dotted lines are linear trendlines for both conditions. Both results have a linear relation with time (doses). That means the disinfection efficacy increases with dose. However, by comparing the disinfection efficacy at the same time points (same dose, 0.5 and 1.0 s), it seemed the log reduction of the continuous mode test was higher than that of pulsed cyclic mode. What caused this difference? During the testing processes, because these two mode tests were independently conducted, the colony forming unit (CFU) and number of pathogens in the samples were different. Based on these test results, there is a significant effect on the disinfection efficacy depending on CFU of the pathogens. Figure 7 (b) shows some comparison between the test results with CFU. In general, it did not matter whether it was a continuous mode test or pulsed cyclic mode test; the log reductions always increase as the CFU increases. That means that in Figure 7 (a), because the initial number of pathogens (3.2×10^5) applied in the continuous mode test is much higher, the initial number of pathogens (1.93×10^4) in the pulsed cyclic mode test the higher log reduction of continuous exposure is because of the higher initial pathogen number.

Figure 7 (c) shows the relationship between log efficacy with tested CFU. Using at least regression method, a linear trendline equation was obtained: $y=0.1537\ln(x)+1.5672$. The log reduction with the exact same pathogen number (1.93×10^4) used in pulsed cyclic was calculated. The log reductions of continuous mode tests for 0.5s and 1.0s were calculated according to the proportion of 0.2s. After correcting the log reductions, Figure 7 (d) shows the corrected disinfection efficacy comparison between the two modes. It seemed the two lines were very close for both test modes. Therefore, there isn’t significant disinfection difference for the continuous mode and pulsed cyclic mode.



(a)



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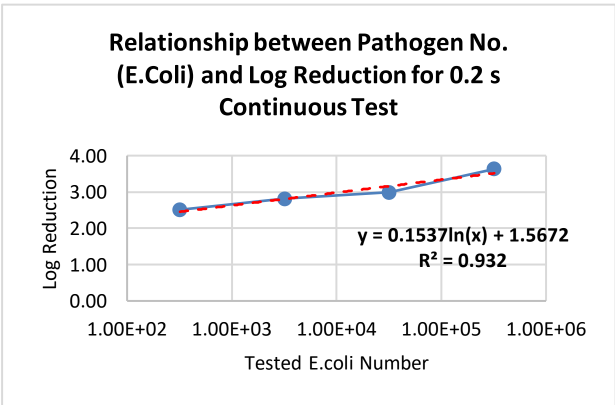
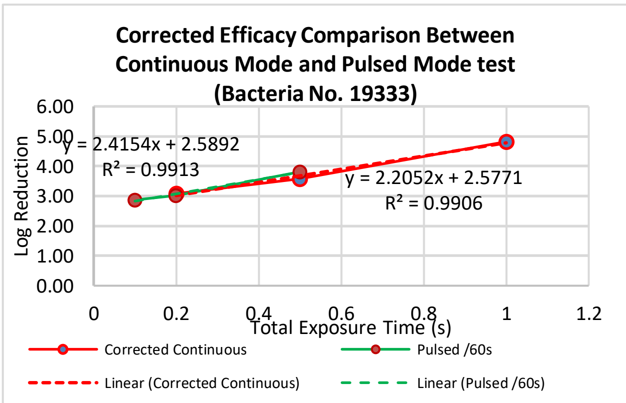


(c)



(d)

Figure 7 The relation of disinfection efficacies between continuous exposure and pulsed cyclic exposure

Usually, the logarithmic reduction of 1 (log reduction=1) means 10% of pathogens survived, i.e. 90% of pathogens were inactivated. D_{90} dosage means the dose can achieve 90% disinfection efficacy. For 2, 3, 4 log reduction, mean 99%, 99.9% and 99.99% of pathogens were inactivated, respectively. Similarly, D_{99}, D_{999}, D_{9999} dosages represent doses needed to achieve 99%, 99.9% 99.99% inactivation of pathogens, respectively. In this work, D_{99} was calculated based on test results of UofT under the zone with UVC intensity 3.78 mW/cm^2. And it will be used to evaluate the disinfection efficacy of this UVC device for various pathogens. The higher the D_{99} dosage, the longer the UVC exposure needed for the handrail surface.

Table 6 shows the tested dose and D_{99} for 4 pathogens. The dose equals the intensity (3.78mW/cm^2) times the total exposure time. Based on these dosages, the D_{99} can be easily obtained when log reduction equals 2. D_{99} dosage for virus HCoV-229 is the highest. That means it will take longer to inactivate HCoV-229E using this UVC device. Based on these tests, the bacteria E.coli is easiest to inactivate.

Table 6 Tested dosages and calculated D_{99} for 4 pathogens

Pathogens	Total Exposure Time	Log Reduction	The Percentage Reduction	Needed UVC Dose (mJ/cm^2)	Calculated D_{99} based on left side measured data	Percentage Reduction	Log Reduction	UVC D_{99} Dose (mJ/cm^2)
E.coli	0.1 s	2.86	99.86%	0.378		99%	2	0.264
S.aureus	0.5 s	2.8	99.84%	1.89		99%	2	1.35
HCoV-229E	1.2 s	2.8	99.85%	4.536		99%	2	3.236
HCoV-OC43	0.4 s	2.2	99.3%	1.512		99%	2	1.375

Table 7 shows the time the UVC device requires to inactivate 99% of the 4 pathogens. This has been used to estimate D_{99} for a 30m escalator handrail on a unit running at 0.5m/s. In this case the escalator needed 3 minutes running to inactivate 99% E. coli, 14 minutes for S. aureus and HCov-OC43, and 32 minutes for HCoV-229E.

Table 7 The required time of the UVC device to inactivate for 4 pathogens

Pathogens	Needed handrail running cycles to kill 99% of pathogens	Time/cycle (minute/cycle)	Time to kill 99% of pathogens (minutes)
E.coli	3	1	3
S. aureus	14		14
HCoV-229E	32		32
HCoV-OC43	14		14

5 CONCLUSIONS

The UVC distribution, intensity, and dose of the new UVC device on an escalator handrail surface was clearly analyzed by combination of a measurement and FEA simulation method. The relationship of intensity and dose between the simulated values and real (measured) values was developed. After analyzing the test results from UofT for bacteria E. Coli, the disinfection efficacy of the UVC device with pulsed cyclic exposure time didn’t have a significant difference with the equivalent continuous exposure time. On the handrail surface, UVC intensity and dose distribution is not uniform. The top surface of the handrail is closer to the UVC device (LEDs), therefore it receives a higher dose of UVC and consequently the disinfection efficacy is higher on the top surface. D_{99} for 4 pathogens was obtained. It was found that the times required for inactivating 99% of various pathogens on the handrail top surface is different for each pathogen. For example, it needs a total of 3 minutes of escalator handrail cycling to kill 99% of E. coli; it needs 32 minutes of the handrail running (cycles) to inactivate 99% of CoV-229E; and it needs 14 minutes of the handrail running (cycles) to inactivate 99% of both S. aureus and CoV-OC43.

6 REFERENCES

[1] W. Kowalski, Ultravilot Germicidal Irradition Handbook, Springer, New York, 2009.

[2] https://www.amca.org/educate/articles-and-technical-papers/amca-inmotion-articles/uv-c-for-hvac-air-and-surface-disinfection-2.html

[3] M. Biasin, A. Bianco, G. Pareschi, A. Cavalleri, C. Cavatorta, C. Fenizia, P. Galli, L. Lessio, M. Lualdi, E. Tombetti, A. Ambrosi, E. M. A. Redaelli, I. Saulle, D. Trabattoni, A. Zanutta, & M. Clerici., "UV C irradiation is highly efective in inactivating SARS CoV 2 replication", March 18, 2021, Scientific Reports (nature.com)

[4] Yin R, Dai T, Avci P, Jorge AE, de Melo WC, Vecchio D, et al. Light based anti-infectives:Ultraviolet C irradiation, photodynamic therapy, blue light, and beyond. Curr Opin Pharmacol. 2013;13:731–62.

[5] Application Note: Disinfection with UV-C LEDs-Würth Elektronik.

[6] Selecting the UV LED Wavelength for Purification Applications — LED professional - LED Lighting Technology, Application Magazine (led-professional.com)

[7] COMSOL - Software for Multiphysics Simulation

[8] Raeiszadeh M, and Adeli B, "A Critical Review on Ultraviolet Disinfection Systems against COVID-19 Outbreak: Applicability, Validation, and Safety Considerations", ACS Photonics. 2020 Oct 14

BIOGRAPHICAL DETAILS

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Benjamin Hatton is an Associate Professor in the Department of Materials Science and Engineering at the University of Toronto. His group investigates fabrication methods for surface topographies, antimicrobial materials, microfluidics, nano/micro porous layers, smart materials, non-fouling biomaterials, and bio-inspired materials. Prof. Hatton currently has 50 peer review publications, 15 patents (and applications).

Vibration Signature and the Application of Intelligent Pattern Recognition in Detection and Classification of Damage in Automatic Power Operated Lift Doors

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Keywords: Lift Doors, Pattern Recognition, Damage, Fault, Maintenance.

Abstract. The majority of faults in lift installations occur in the door (entrance) systems. Wear and tear of the door operator mechanism and the door system components/ subsystems will result in defects that lead to damage which in turn leads to faults, understood as a change in the door system that produces an unacceptable reduction in the quality of its performance. The research presented in this paper involved the development of an experimental lift door stand to collect vibration signature datasets corresponding to a range of typical damage classes that occur in lift door systems. The installation comprises single speed doors (single panel side opening and two panel centre opening) as well as two speed doors (two panel side opening and four panel centre opening). Once the data are collected the vibration features are extracted and used in supervised learning to train the artificial neural networks designed to recognize patterns and to classify damage. The results obtained demonstrate excellent performance of the network with very high percentage of correctly classified damage classes involved. The work completed so far forms the basis for the development of decision stage algorithms to analyze the results from the pattern recognition and to decide about appropriate maintenance actions required.

1 INTRODUCTION

Fault data collected from lift installation sites show that the majority of faults occur in door (entrance) systems [1]. The lift entrance system comprises landing (hoistway) doors and car doors. Most elevators intended for passengers have fully automated power-operated doors. The standard arrangement for automatic power operation involves a 'master' operator, a self-contained electric motor driven unit mounted on the car top. The unit is coupled mechanically with the car door through a linkage system, a toothed belt or similar device to achieve the speed profile for opening and closing of the doors. The door motion is electronically controlled. A block diagram of an electronically controlled door operator is shown Fig. 1 [2]. In this arrangement the microprocessor unit senses the position of the doors (usually via a simple optical encoder mounted on the motor, as shown), and controls the speed of the motor in accordance with the position of the doors, as required by an inbuilt speed/position profile held in the microprocessor memory. The doors can operate at different speeds under different circumstances.

Wear and tear of the door operator mechanism and the door system components/ subsystems will result in damage and the system is no longer operating in its ideal condition (but can still function satisfactorily). This in turn will lead to a fault, when the system can no longer operate satisfactorily (a change that produces an unacceptable reduction in quality) [3].

There should be a relevant maintenance strategy in place for planning and implementing repairs or replacements of damaged/ faulty components/ subsystems in lift systems [4]. The preferred strategy is predictive maintenance where the condition is monitored (while the system is operating) and any damage is detected and identified very early before the fault is developed. The condition monitoring then predicts when maintenance should be performed.

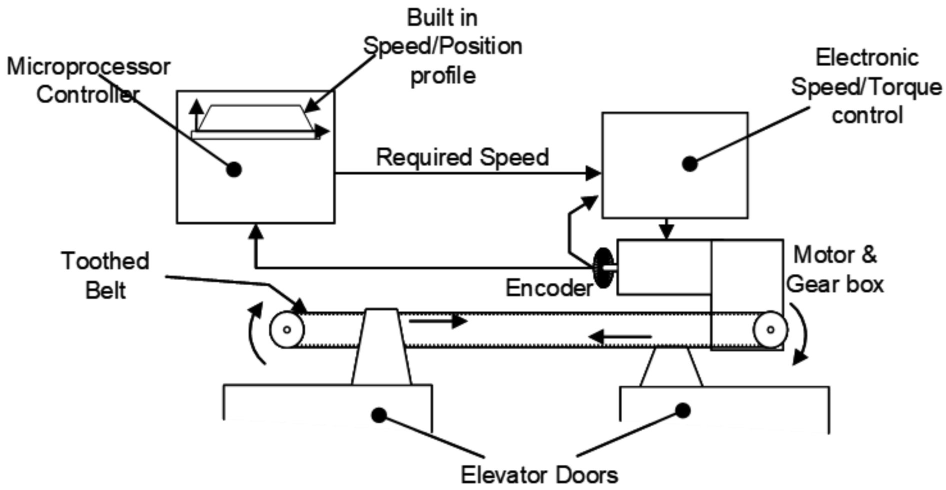


Figure 1 Automated power-operated door: an electronically controlled door operator

Bearing this in mind, the following hierarchical structure and the method levels in damage identification should be followed [3]:

1. Detection: the method gives a qualitative indication that damage might be present in the system.
2. Localisation: the method gives information about the probable position of the damage.
3. Classification: the method gives information about the type of damage.
4. Assessment: the method gives an estimate of the extent of the damage.
5. Prediction: the method offers information about the safety of the system, and possibly estimates a residual life.

In this paper the application of machine learning (ML) techniques and Artificial Neural Networks (ANN) algorithm based on vibration signal data for damage detection and classification in lift door systems is investigated. An experimental test rig to generate a comprehensive set of vibration test data corresponding to a range of typical damage classes that occur in lift door systems has been developed. Once the data are collected, suitable vibration features are extracted and used in supervised learning to train the ANN designed to recognize patterns and to classify damage.

2 EXPERIMENTAL SETUP AND VIBRATION DATA

The experimental lift door stand to carry out tests and collect vibration data has been developed. The stand has been designed to accommodate various types of lift doors: single speed doors (single panel side opening and two panel centre opening) as well as two speed doors (two panel side opening and four panel centre opening). Fig. 2(a) shows two speed two panel side opening doors fitted in the stand frame. The door motion and vibrations have been monitored by using B&K accelerometer sensors (see Fig. 2(b)) attached to the door structure at various locations. The analogue signals from the accelerometers are recorded by using the B&K LAN-XI recorder platform. Three LAN-XI modules (see Fig. 2(c)) with four input channels each are applied.

The door speed / acceleration and jerk are monitored during/ jerk profiles are determined by integrating / differentiating the acceleration signals obtained from sensors mounted on the car and hoistway door sets, respectively (see Fig. 3). The time records of vibration responses are postprocessed and then used in supervised learning to train the ANN, designed to recognize patterns and to classify damage. The raw time data sets are pre-processed and normalized (see Figure 4(a)). These are post-processed to develop spectrograms (see Fig. 4(b)). The cepstrogram (see Fig. 4 (c)) is then calculated to extract its real coefficients as features to be used in the neural network pattern recognition (NNPR) algorithm.

(a)

(b)

(c)

Figure 2 Experimental setup

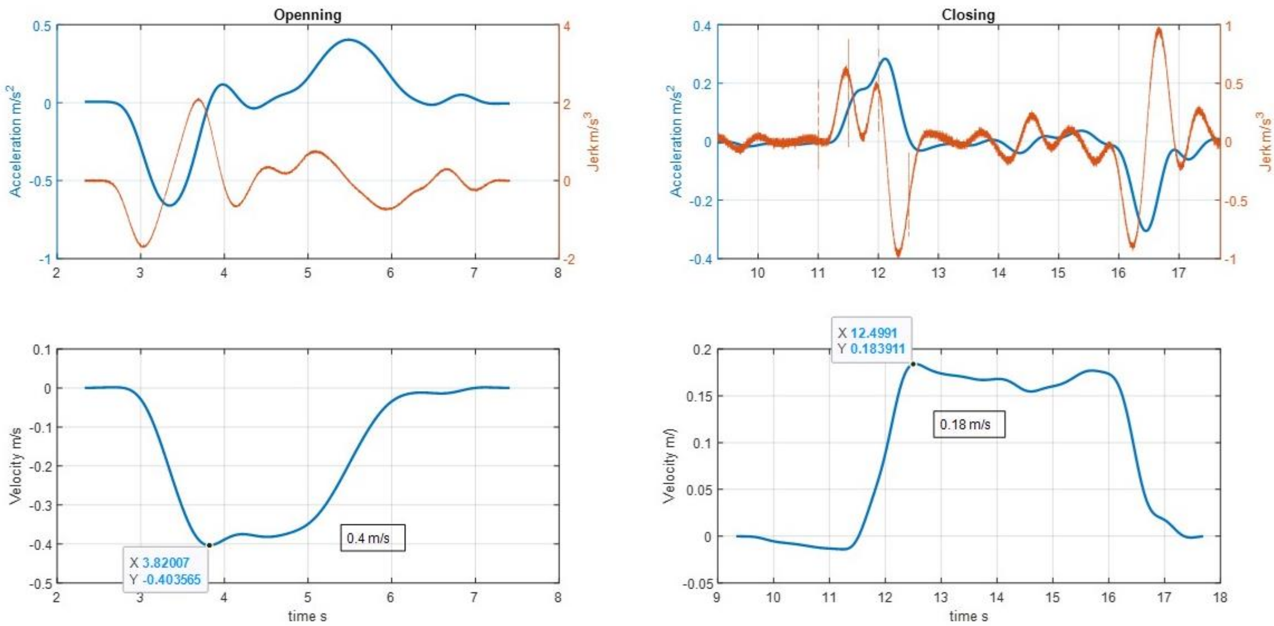


Figure 3 Door motion jerk / acceleration and speed time profiles

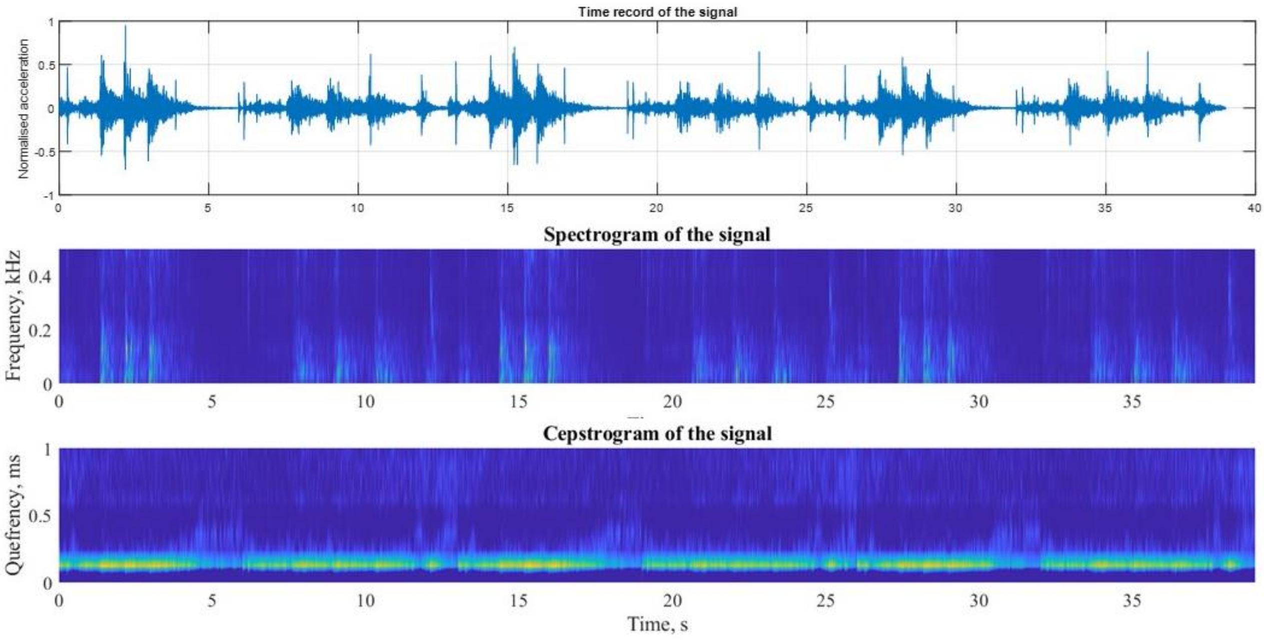


Figure 4 Single panel side opening door vibration data: (a) normalized acceleration signal, (b) spectrogram, (c) cepstrogram

3 DAMAGE PATTERN RECOGNITION BY USING ARTIFICIAL NEURAL NETWORK ALGORITHM

Eight main categories of ‘damage’ are considered (and are referred to as ‘damage classes’). These are as listed in Table 1.

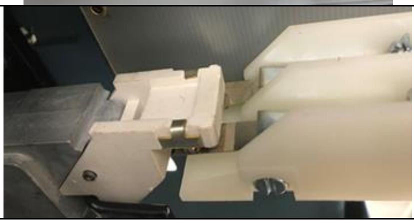
Supervised machine learning is applied to develop a NNPR algorithm to classify the damage. In the algorithm an input data set (based on the cepstrogram features) is classified into a set of target categories (the target dataset comprises vectors with a sequence of 0, 1 elements, see Table 1). The algorithm needs to have prior knowledge and it is necessary to construct examples of data corresponding to each damage class. Thus, a *training set* of data/measurements vectors associated uniquely with each class is necessary. Consider an example in which a shallow neural network is used. The network is developed by using the MATLAB ‘nprtool’ app [5]. The network is a two-layer feed-forward network (see Fig. 5(a)).

Fig. 5(b) shows the confusion matrix from testing after the training. This matrix demonstrates the following:

- the rows correspond to the predicted (output) class,
- the columns correspond to the true (target) class,
- the diagonal cells correspond to samples that are correctly classified,
- the off-diagonal cells correspond to incorrectly classified samples,
- the column on the far right shows the percentages of all the examples predicted to belong to each class that are correctly classified (positive predictive values) and incorrectly classified (false discovery rates),
- the cell in the bottom right of the plot shows the overall accuracy.

The test confusion matrix indicates the classification performance. The overall accuracy is 97.9% which demonstrates excellent performance of the NNPR algorithm.

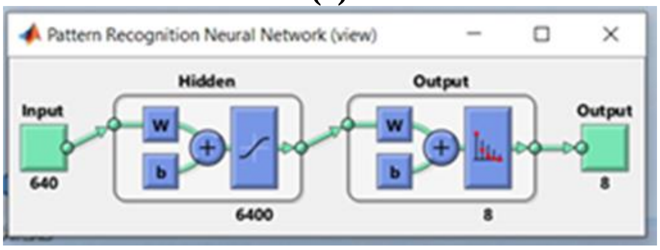
Table 1 Damage Classes

Class No.	Description / target vector	Deatails
1	**No damage** [1 0 0 0 0 0 0 0]^T	**Baseline state of the door installation**
2	**Car door roller with damage** [0 1 0 0 0 0 0 0]^T	
3	**Hoistway door roller with damage** [0 0 1 0 0 0 0 0]^T	
4	**Door panel sill guide contaminated** [0 0 0 1 0 0 0 0]^T	
5	**Damaged interlock rollers** [0 0 0 0 1 0 0 0]^T	
6	**Low tensioned (loose) door drive belt** [0 0 0 0 0 1 0 0]^T	
7	**Damaged belt tooth** [0 0 0 0 0 0 1 0]^T	
8	**Interlock misalignment** [0 0 0 0 0 0 0 1]^T	

4 CONCLUSIONS

The results obtained demonstrate excellent performance of the network with a very high percentage of correctly classified damage classes investigated. The work completed so far forms the basis for further work. This will involve the development of decision stage algorithms to analyze the results from the pattern recognition and to decide about the appropriate maintenance actions required.

(a)



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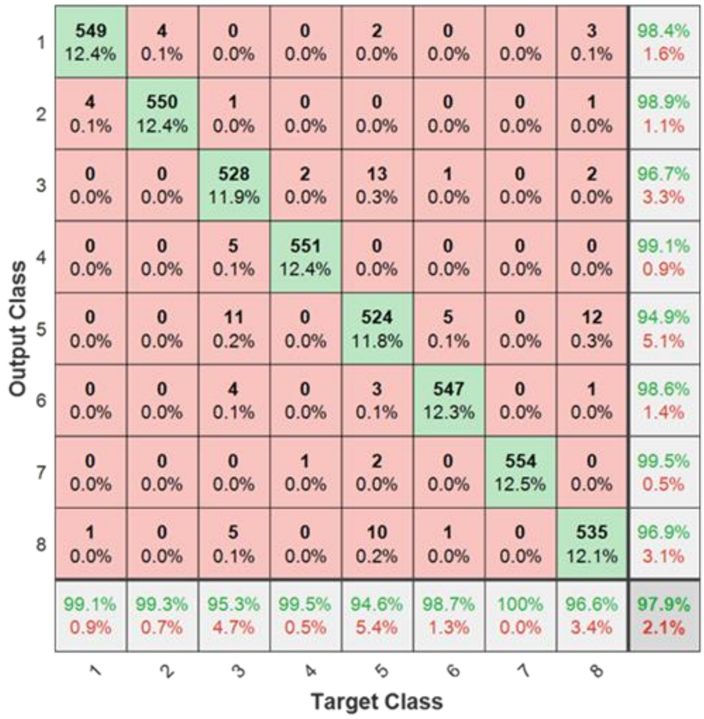

Figure 5 (a) neural network, (b) test confusion matrix

ACKNOWLEDGEMENT

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REFERENCES

[1] A. Torres Perez, S. Kaczmarczyk and R. Smith, "Automatic Fault Detection and Classification in Lift Door Systems Using Vibration Signal Features". *In: Rizzo, P., Milazzo, A. (eds) European Workshop on Structural Health Monitoring. EWSHM 2020. Lecture Notes in Civil Engineering,* Vol 128. Springer, Cham. https://doi.org/10.1007/978-3-030-64908-1_71.

[2] J.P. Andrew and S. Kaczmarczyk, *Systems Engineering of Elevators*. Elevator World, Mobile, AL (2011).

[3] K. Worden, J.M. Dulieu-Barton, An Overview of Intelligent Fault Detection in Systems and Structures. *SHM,* 2004, Vol 3(1), 85–98.

[4] British Standards Institution, *Maintenance for lifts and escalators — Rules for maintenance instructions.* BS EN 13015:2001+A1:2008.

[5] www.mathworks.com (Accessed 12 May 2022)

BIOGRAPHICAL DETAILS

Dr Stefan Kaczmarczyk is Professor of Applied Mechanics and Postgraduate Programme Leader for Lift Engineering at the University of Northampton, UK. His expertise is in the area of applied dynamics and vibration with particular applications to vertical transportation and material handling systems. He has published over 100 journal and international conference papers in this field. He is a Chartered Engineer, elected Fellow of the Institution of Mechanical Engineers and a Fellow of the Higher Education Academy.

Dr Rory Smith has over 49 years of experience in all aspects of the lift industry including sales, installation, maintenance, manufacturing, engineering, research & development. He has worked for ThyssenKrupp Elevator for the last 23 years. Prior to becoming involved in ThyssenKrupp's Internet of Things, he was Operations Director, ThyssenKrupp Elevator Middle East. His scientific interests include: operations management, high rise - high speed technology, ride quality, traffic analysis, dispatching. To date he has been awarded numerous patents in these areas and has many pending patents.

Mateusz Gizicki is a postgraduate researcher at the University of Northampton. He has a bachelor's degree in Mechanical Engineering from the University of Northampton and is currently working towards achieving his doctorate in the area of Multi-Physics and Computational Fluid Dynamics. He is an Associate Member of the Institution of Mechanical Engineers and has experience in research and development in the industry environment as well as academia. In addition, he has recently completed the Knowledge Transfer Partnership project as a KTP Associate, which combined management skills with complete product development.

1927 - The Year That Set the Direction of Traction Lift Engineering for a Century

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Keywords: lift, history, traction, lift engineering

Abstract. Nearly a century ago in 1927, F. Hymans and A. H. Hellborn published their famous book "*Der neuzeitliche Aufzug mit Treibscheibenantrieb*" (*Modern elevator with traction sheave drive)*, which had a major impact in the introduction of traction sheave lifts to the European Market and laid the groundwork of modern lift engineering. The book explains the function of traction sheave lifts, the theory of traction calculation and several other key principles of lift engineering.

A less known, but likewise important book, was published on the same year by H. Donandt. His dissertation "*Über die Berechnung von Treibscheiben im Aufzugbau" (On the calculation of traction sheaves in elevator construction)* touched some of the same topics as Hymans' and Hellborn's book, but merits independent recognition.

A major handicap in understanding the background of modern lift engineering is that to this day neither of the books have been translated into English for the wider lift engineering audience.

This article gives an overview on the content of these books and explains how these two books differ in their approach. The article also briefly introduces the authors and the historical framework behind these books. Sections of these books that have had larger significance to this day are given specific attention.

1 LIST OF SYMBOLS

α	Undercut angle	b	Acceleration/Deceleration of the lift
γ	Angle of submersion of rope in the groove (Also wedge angle for wedge shape groove)	d	Rope diameter
φ	1-sided contact angle between the rope and the groove	D	Traction sheave diameter
μ	Apparent friction coefficient (friction factor)	N	Normal force
μ_0	(Actual) Friction coefficient	g	Gravity acceleration
		p	Groove pressure
		S	Rope tension
		W	Friction force

NOTE! There is some inconsistency in the symbols in figures due to original source images.

2 INTRODUCTION

The later part of 19th century and the beginning of 20th century was a period of fast development in the building and industrial sectors. As construction techniques improved and buildings got taller, so did the demand for higher lift travels. The USA had assumed a leading position in the construction of tall buildings, and it was only logical that the Americans were also in the forefront of lift engineering. A key paradigm shift was the transition from drum lifts to traction lifts, which changed the lift industry as profoundly as the invention of the safety gear a half-century earlier.

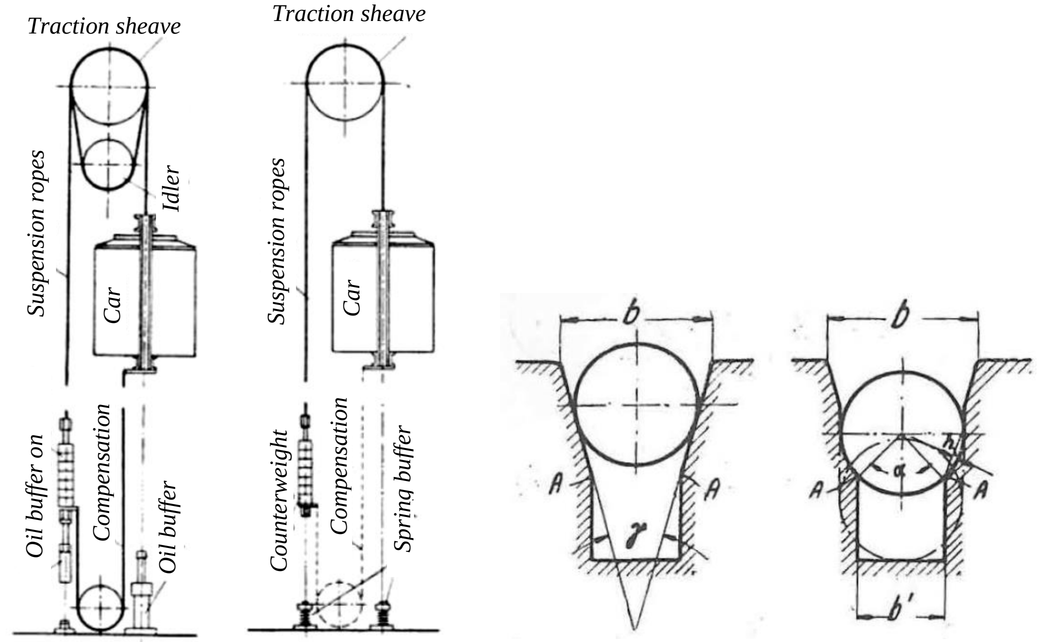
The transition to traction lifts had an impact on the way lifts were engineered and there was a need to raise awareness of these new engineering principles. A book by F. Hymans and A. H. Hellborn "*Der neuzeitliche Aufzug mit Treibscheibenantrieb*" (The modern elevator with traction sheave drive) rose to the occasion and became a cornerstone for lift engineering for decades. The book is not without shortcomings though. As the writers were working for Otis, revealing the full extent of their knowledge was not necessarily within their interest. One can speculate that the motivations of two Otis employees to write a book in German was not just raise the general level of knowledge, but also to advertise the state of American engineering and to gain wider acceptance to their engineering principles to help the sales of Otis products overseas.

Already prior to the publication of *Der neuzeitliche Aufzug*, the benefits of traction lifts had been seen in Germany. To study some of the key engineering problems, a doctoral dissertation was launched in the Technical University of Karlsruhe. One of the supervisors was Dr. G. Benoit, who was an influential figure in the German lift association at the time. This dissertation by H. Donandt was published at the same time as *Der neuzeitliche Aufzug* and addressed some of the same topics as Hellborn and Hymans, but without the ulterior motives of a commercial nature. Donandt's publication has had much less recognition than his American counterpart but some of his conclusions have had long lasting implications.

3 HISTORICAL CONTEXT

In the introduction of *Der neuzeitliche Aufzug* it is mentioned that traction sheave lifts were first introduced in the American market circa 1890, but at that time they could not compete with drum type lifts due to the double wrap construction and lower market needs [1]. In an earlier article by Hellborn it is mentioned that "full-wrap traction" (double wrap) (Fig. 1a) had been used in New York skyscrapers for years and that "half-wrap traction" (single wrap) (Fig. 1b) had been found in England for a long time [2]. The year 1919 is also referenced as a turning point from drum type to traction type lifts.

In his dissertation Donandt is making references to earlier publications concerning Koepe hoist [3]. The Koepe hoists are used in the mining industry and are also based on the traction sheave principle. The Koepe hoist had been patented in many European countries in 1887 [4], however, the traction sheaves with wood and leather inserts used in Koepe hoists made the design unfeasible for lift applications.



1a) Double wrap 1b) Single wrap 1c) Wedge groove 1d) Undercut groove

Figure 1 Illustration of double and single wrap lifts [1] **and wedge and undercut rope grooves** [3].

Although a lot of proprietary experimental data must have been available in 1927, a theoretical basis was needed quantify the traction capacity. This was the problem that Hymans, Hellborn and Donandt set out to resolve[1]. Attention was especially paid to the single wrap configuration where traction is not so abundantly available, and to the relatively novel undercut rope groove design (Fig. 1d).

The most well-known of the three authors is undoubtedly Frederick (Fred) Hymans and his biography is well covered in two articles by Gibson [5] [6]. Here it suffices to say that Hymans made an extensive career in OTIS and American Society of Mechanical Engineers (ASME), published two books in addition to the *Der neuzeitliche Aufzug*, wrote several articles published in ASME Transactions and within OTIS internally and participated actively in overall technical discourse during the first part of 20th century.

Less is known about Hymans' co-writer Axel Hellborn. Based on Gray [7] he appears to have only made a short career in OTIS, but it is worthwhile to notice that the article that predates *Der neuzeitliche Aufzug* was written solely by Hellborn, albeit he gives credit to Hymans in one footnote. Later – after the Second World War - Hellborn was contracted by the Finland Industry Delegation War Compensation (Soteva) to rationalize industrial production across multiple companies (incl. KONE), to improve Finland's ability to meet its obligations to the Soviet Union [8], but there are no records of his involvement in lift engineering since *Der neuzeitliche Aufzug*.

Prior to his dissertation Hermann Donandt worked for R. Stahl A.G. in Stuttgart where he had his introduction to the lift industry [3]. Later he made a career in the Karlsruhe Institute of Technology (KIT), where his supervisor Georg Benoit had founded a chair for lift and transport machines. Donandt is credited in particular for rebuilding the department after the Second World War. He was the director of Institute for Material Handling and Logistics in KIT during 1947 – 1966. Industry legend Klaus Feyrer, for instance, studied there during his leadership period. He was also influential in the development of the lifts to the Moscow TV-tower, which were a substantial engineering achievement at the time [9]. In addition, he acted as director of the testing centre of the German lift committee, was involved in the development of safety gears and carried out studies into stresses in wire ropes [10].

4 THE MOST RELEVANT TOPICS

Rope traction is obviously the main topic that both books have in common, but there are other related areas where comparison is possible. *Der neuzeitliche Aufzug* also covers areas which are not part of Donandt's dissertation, including a section contributed to the standardization of the lift designs.

4.1 Rope traction theory

In his forewords, Donandt writes that "*the previous publications do not offer sufficient background in form or content for calculation of elevator with traction sheave,"* referring primarily to literature concerning Koepe hoist systems and the framework of his dissertation is to correct this deficiency. The book by Hellborn and Hymans was not available to him at the time of writing.

4.1.1 The force ratios

It is interesting to note that already in his introduction to the traction theory, Donandt mentions the dynamic rope force ratios over the traction sheave, which indicates that this was an acute problem in traction dimensioning. It is also here that the first link to present day lift standards can be seen; both books conclude – based on slightly different argumentation - that a properly dynamically dimensioned lift can be safely overloaded with about 1/3 of the nominal load and that if the lift speed is not too high (and overload condition not too frequent), the small possible slip during acceleration would not be harmful. This is still reflected in chapter of A17.1 concerning the carrying of one-piece load [11].

[1] The significance of rope traction of lifts at the time is highlighted by the fact that C.C. Clymer also published an article in November of 1927 in General Electric Review, which addressed the topic.

4.1.2 The traction factor

Concerning the traction factor, Donandt commences from equations available for Koepe hoists at the time and uses a finite wedge-shaped linear object placed in a corresponding groove as a basis of his derivation. Donandt specifically mentions that he is aware of Hymans's formula (Eq.1) from Hellborn's article, but that the derivation was not commonly known.

$$\mu = \mu_0 \frac{4(1 - sin\alpha/2)}{\pi - \alpha - sin\alpha} \tag{1}$$

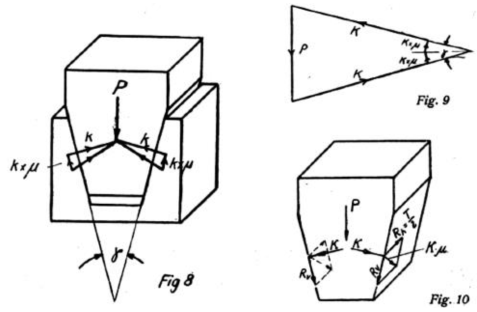


Figure 2 The engagement of wedge-shaped linear object placed in corresponding groove [3].

Donandt first formulates the equation for a round rope in wedge shape groove and then solves his equation for the specific case of circular rope seat (Eq. 2). In case of a rope positioned fully in the groove $\frac{\alpha}{2} + \varphi = \frac{\pi}{2}$, the equation can be simplified to Hymans's formula (Eq.1).

$$\mu = \frac{4 \cdot \mu_0 \cdot \left[\sin\left(\frac{\alpha}{2} + \varphi\right) - \sin\frac{\alpha}{2}\right]}{sin(\alpha + 2\varphi) - sin\,\alpha + 2\varphi} \tag{2}$$

In comparison to *Der neuzeitliche Aufzug*, it is interesting to note that Donandt goes to some lengths to justify the usage of uncompressible rope in his derivation by presenting an alternative derivation for a compressible rope, referencing an earlier publication "*Die Drahtseilfrage" (The wire rope question)* [12], where the topic is discussed, and later reflecting his results against both formulas. Figure 2 shows the engagement of a wedge-shaped linear object in a corresponding groove, which Donandt used in his derivation for elastic ropes.

The approach in *Der neuzeitliche Aufzug* is somewhat different. Overall, the topic of specific pressure in the groove is considered first and the derivation is based directly on a rope in an undercut groove. The basic definitions are listed in the beginning as follows:

1. The rope groove forms a non-elastic surface
2. The load does not cause any change in the cross-section of the rope
3. The rope can be considered as a smooth cylinder.

The fourth assumption is that vertical component of pressure must have the same value at each contact point because the vertical wear is observed to be the same everywhere (see 4.1.3).

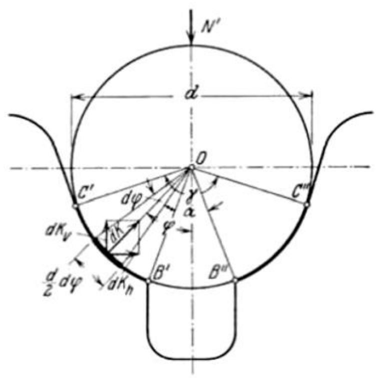


Figure 3 The determination of the size of the contact forces [1]

The derivation starts by determining the equilibrium conditions for a finite rope element, which is under the influence of the contact forces between rope and groove and the compressive force (Fig. 3). This gives the possibility to derive the magnitude of compressive force and, based on the relationship imposed by the four earlier assumptions, to determine the relationship (Eq. 3) between pressure, rope tension (*S*), groove geometry and the diameters of the rope (*d*) and the undercut traction sheave (*D*). To solve the formula for the friction force against rope slip (*W*), this is then integrated over the entire contact length (Eq. 4).

$$p = \frac{8 \cdot \cos\varphi}{\gamma - \alpha + \sin\gamma - \sin\alpha} \cdot \frac{S}{d \cdot D} \tag{3}$$

$$W = \mu_0 \cdot d \int_{\alpha/2}^{\gamma/2} \frac{8 \cdot \cos\varphi}{\gamma - \alpha + \sin\gamma - \sin\alpha} \cdot \frac{S}{d \cdot D} \cdot d\varphi = 8\frac{S \cdot \mu_0}{D} \cdot \frac{\sin\gamma/2 - \sin\alpha/2}{\gamma - \alpha + \sin\gamma - \sin\alpha} \tag{4}$$

Since by definition the normal force over the traction sheave can be given as $N = \frac{2S}{D}$, the friction force is $W = \mu \cdot N$and as $\gamma = \pi$ for a rope positioned fully in the groove, the later equation can be transformed using the equation given in Hellborn's article (Eq.1) for the relationship between actual and apparent coefficient of friction.

It is particularly important to note that the authors are critically aware of the limitations of their derivation. Firstly, they discuss the impact of the size of the undercut and conclude that with centre angle values above 120° the groove geometry does not correspond to the derivation anymore. Secondly, the influence of assumed rope shape versus the actual contact between the groove and individual wires within the rope strand is considered and it is proposed that a correction factor should be applied based on the construction of the rope.

4.1.3 The specific pressure between rope and groove

As mentioned, *Der neuzeitliche Aufzug* treats the topic of specific pressure before deriving the traction factor. The chapter starts by declaring that the destruction of the grooves is caused by wear, and wear is caused by rope creep and rope slip. It is also stated that since the vertical wear of the groove is the same everywhere, the vertical pressure component ($p = p_0 \cos\varphi$) must also be the same at each point of contact.

Since the presumption is that the wear is determined by the number of roundtrips, the lifts are classified in to four distinct groups depending on their usage. These classes are 1) Passenger lifts for 8-10 hours of usage per day, 2) Passenger lifts for intermittent traffic, 3) Goods lifts similar for intermittent traffic, but longer loading times and 4) Goods lifts that are used rarely.

Subsequently, the permissible surface pressure is given for each class based on experiments (Fig. 4), but the details of these experiments are not given. It is also stated that these limits apply for round stranded ropes with a Regular lay and that for Lang's lay these values can be exceeded by 25%.

Later, an adaptation of these limits was applied in German TRA 003 lift regulation [13] from where it got copied to EN 81-1 for a brief period between 1986 and 1989.

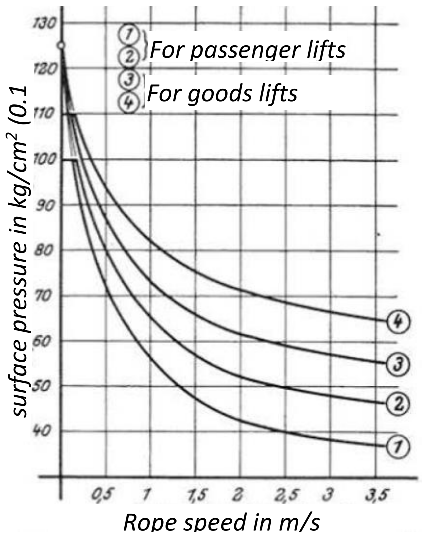


Figure 4 Permissible surface pressure between rope and groove for a round strand rope with Regular lay and groove rim from mixture of grey cast iron and scrap steel [1]

According Donandt, the concept of limiting the permissible groove pressure was relatively new at the time and the conventional approach was to select quantity of ropes solely based on strength calculations. When Donandt was writing his dissertation, he did not have the full explanation of *Der neuzeitliche Aufzug* available, however he made some observations based Hellborn's article. He was concerned that the pressure (at point $\alpha/2$) used in the derivation of pressure formula is not changing in relation to the width of the undercut and he had doubts about the pressure distribution assumption. He also raises questions about the impacts of cross-sectional resistance, wire thickness and strand construction of the ropes, as well as the impact of the hardness of the sheave, but concludes that these questions can only be answered by obtaining more experimental data.

More significantly though, Donandt claims, based on his own experiments, that rope slip alone cannot explain the wear of traction sheave. For his tests, he attempted to create a rope seat in a traction sheave by slipping a rope over it but had great difficulties in achieving symmetric wear as seen in Figure 5. As a supplementary explanation he proposes that a part of the wear mechanism are the changes in the material due to load changes caused by the movement of the lift.

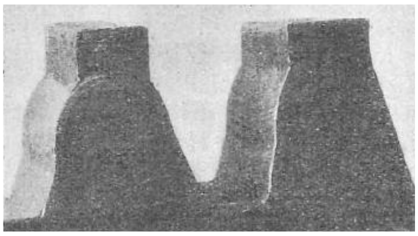


Figure 5 Asymmetric wear documented by Donandt [3].

But while there is some disagreement on the wear mechanism and on the determination of the permissible pressure, Donandt concludes that it was advantageous not to let the pressure become too high due to rope and sheave lifetime considerations.

4.2 Rope safety factor

In the beginning of the 20th century the question 'which safety factor should be applied?' was very much open. Donandt reports that there was an on-going discussion in the German lift association whether to base the safety factor calculation solely on the tensile stress or to also take the bending stress into account. *Der neuzeitliche Aufzug* gives a table with a foreword that safety factors applicable in USA can be read directly from the maximum rope load curves. As reference, Grierson [14] reports that in England the safe working load was one twentieth of the breaking load and explains that the differences in safety factor are at least partly due to rope materials used in different markets.

Table 1 Rope safety factor according Hellborn and Hymans [1]

	Lifting speed (m/s)	0.5	1.0	1.50	2.0	2.50
Min. safety factor:	Passenger lifts	8	8.6	9.2	9.7	10.2
	Freight lifts	7	7.6	8.2	8.65	9.1

The significance of safety factor in conjunction with the introduction of surface pressure limits is that both Donandt and Hellborn together with Hymans conclude that safety factor calculation becomes partially redundant if pressure limits are followed. Donandt goes as far as to formulate a relationship between the safety factor of contemporary German ropes and undercut angle for different d/D-ratios (Fig 6).

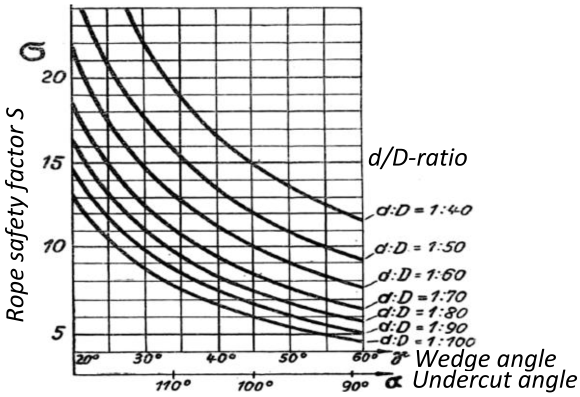


Figure 6 A safety factor chart for all loads and rope-to-traction sheave-ratios [3].

An interesting reflection to modern European regulations is that groove pressure is no longer considered, and it has been replaced by a complicated calculation for a minimum rope safety factor [15]. This compulsory requirement in practice only influences hoisting configurations with a large amount of relatively small pulleys, while in many applications, such as high-rise, only the absolute minimum safety factor of twelve has relevance. Also, this calculation does not consider decades of development in rope technology, which may lead to excessive groove pressure [16].

4.3 Coefficient of friction

Der neuzeitliche Aufzug explains explicitly the difference between apparent and actual friction coefficient and how the relationship is formulated. As already mentioned, the formula (Eq. 1) was known to Donandt from Hellborn's earlier article. To verify their friction calculation method, Hellborn and Hymans present measurement results done with ordinary round strand ropes using two different sized traction sheaves with different undercuts (Fig. 7). For the rope slip results, the sliding speed was 2.5 m/s. Their conclusion of these results can be summarized as follows: The difference in friction between before and after the rope slip is due to lubrication, which is effective only after there is movement between the rope and the sheave and the tension ratio becomes independent of the load at relatively high loads due to the stiffness of the rope (the rope diameter used in the tests is not specified). Finally, they compare actual friction coefficient values from these calculated tests (μ_0 = 0.080 and 0.083) to earlier tests conducted with semi-circular groove (μ_0 = 0.084) and present this as proof of the correctness of their mathematical analysis.

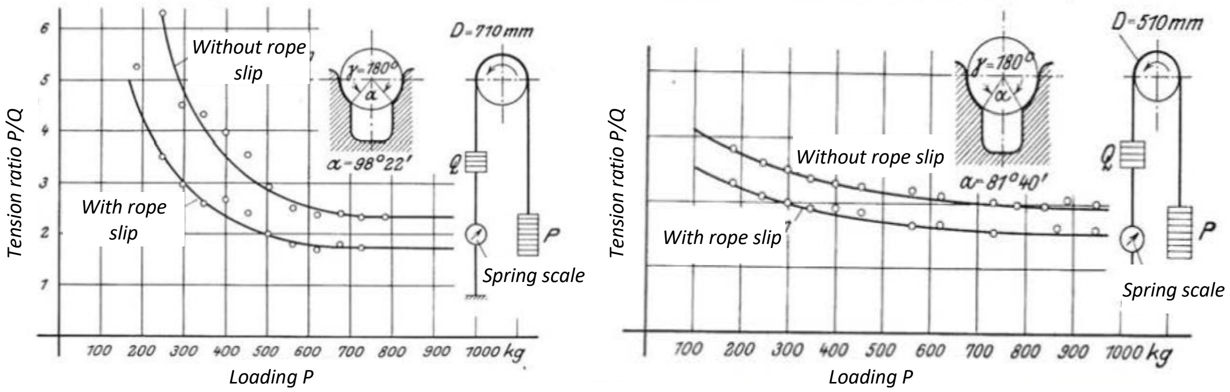


Figure 7 Friction test arrangement and results by Hellborn and Hymans [1]

While *Der neuzeitliche Aufzug* treats the topic of actual friction coefficient relatively briefly, a substantial portion of Donandt's dissertation is focusing on tests to understand the dependence of rope friction on four parameters: surface pressure, lubrication, sliding speed and surface quality. His test arrangement is in principle similar to Hellborn and Hymans, but one difference is clear from the onset; the diameter of the traction sheave is only 400 mm, and with a 16 mm rope Donandt is only able to achieve d/D-ratio of 25. But he states - in direct contradiction to Hellborn and Hymans - that the test results did not show that the rope stiffness would be influential even with small loads.

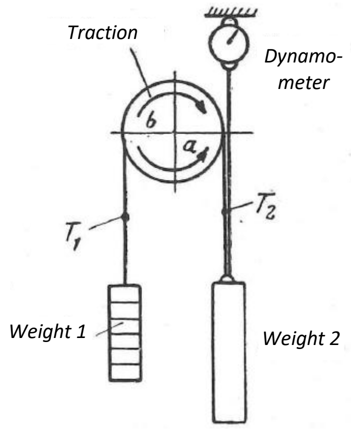


Figure 8 Friction test arrangement by Donandt [3]

Donandt makes the following prepositions based on these four testing parameters:

1. The question of the dependence of μ_0 on the diameter of the ropes and on the size of the support surface is the same as the question of the dependence on **the pressure**. In otherwise unchanged conditions, an increase of rope diameter or support surface will only result in a reduction of the specific pressure. The study of different rope diameters can thus be ignored.
2. Dependence of friction on **the lubrication** can only be significant for the state of rest. As soon as the rope begins to slide, the lubricants on the wires and the sheave will be displaced from the contact so that they become ineffective.
3. Concerning **the sliding speed,** it is known that the friction in rest is greater than in sliding. In the normal operation, the friction value at rest is decisive because the rope is in rest in relation to the sheave, but if due to acceleration or braking situation the ropes start to slip, the smaller dynamic friction applies, and it must be taken as a basis for the traction calculations.
4. **The quality of the groove surface** has an influence on the magnitude of friction. The reduction of friction due to running-in is relevant because the initially rough grooves will be smoothened by the ropes over time. The question of whether friction is dependent on the material of the sheave could be seen only when the pressure of the wires became so great that they left impressions in the sheave.

Again, Donandt's second claim is in direct contradiction to the statement by Hellborn and Hymans.

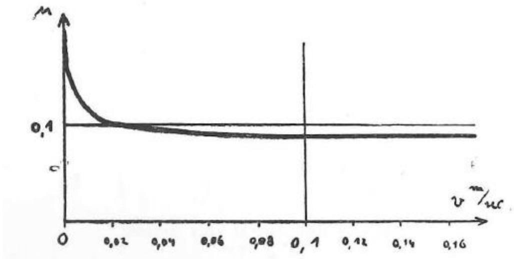


Figure 9 Dependence of friction on sliding by Donandt [3]

After conducting hundreds of individual tests, divided into 21 test sets in three distinct groups, Donandt made the conclusion that the static friction varied between 0.104 and 0.184 and sliding friction between 0.09 and 0.160 for rope speed exceeding 0.1 m/s (Fig. 9). And that the smallest of these values, $\mu_0 = 0.09$, should be used in calculations.

Here, it is interesting to note that according to Gibson the friction coefficient value published in *Der neuzeitliche Aufzug* was widely in use in the lift industry at least during the 1990s (Table 2) [16], and Donandt's value lived on, first in the German lift regulation TRA 003 [13] and later in the European standard EN 81-1:1985. The reason why Donandt's friction coefficient was abolished from later versions of EN 81-1 was the introduction of speed dependent friction coefficient formula, at least partly due to influence by KONE [17]. The speed dependency allowed initial friction coefficient value to be set to 0.1, which is close to Donandt's lower static bound.

Table 2 Rope friction factors by Gibson [16]

Source	μ_0
Otis	0.084
Haughton	0.084
Millar	0.084
Westinghouse	0.094
Schindler	0.094
Dover	0.100
EN 81-1:1985	0.090
EN 81-1:1998 EN 81-50:2020[1]	0.100
[1] Addition by Author	

4.4 Deceleration and acceleration of lifts

Determining the upper bound of the deceleration and acceleration of lifts is a relevant question when determining the needed traction. Also, before the age of computers, it was convenient to produce one calculation that would cover both static and dynamic load cases with the least amount of calculation, which resulted in simplified dynamic factor $\frac{g+b}{g-b}$, where g is the gravity acceleration and b is the acceleration or deceleration.

Table 3 Acceleration/deceleration in respect to lifting speed according to Hellborn and Hymans [1]

v (m/s):	0.65	1.0	1.5	2.0	2.50	3.0	3.5
b (m/s^2):	0.65	0.85	1.15	1.40	1.65	1.88	2.10

Donandt was concerned in particular about the deceleration during braking as the lifts in Germany at the time were also stopped in normal operation by a mechanical brake, which could cause harsh stopping, whereas many contemporary American lifts performed gradual stopping using the motor. The claim is supported by the table from *Der neuzeitliche Aufzug* (Table 3), which gives very specific deceleration rates. After conducting a series of field measurements – including one notoriously unpleasant lift in Stuttgart - Donandt concludes that the maximum deceleration was 0.3 g, but that 0.2 g would be sufficient for traction calculation if dynamic friction coefficient was applied. It should be noted that Donandt's values can also be considered as maximum values for emergency braking condition.

By today's standards any values above ca. 1.4 m/s^2 would be considered excessive in normal use and thus the dependency between speed and acceleration given in Table 3 is no longer relevant.

4.5 Dimensioning of oil buffers

Der neuzeitliche Aufzug contains a wide variety of topics, which are beyond the scope of Donandt's dissertation. One of these topics, which should not be dismissed, is dimensioning of oil buffers, because of its long-lasting implications.

Already prior to the publication of *Der neuzeitliche Aufzug* Hymans had been actively solving design challenges concerning buffers [1] and had written about the buffer stops of lifts published in ASME Transactions in the previous year [18]. He also discussed at length the topic of buffers again in The Electric Elevators, Book I [19] in ca. 1930.

To start with, *Der neuzeitliche Aufzug* makes the statement that tests have shown that greater deceleration than 2.5 g causes discomfort to passengers, and that decelerations above 3 g are considered dangerous, but no further details are provided. Later, in reference to oil buffers, it is mentioned that in general the buffers are designed to decelerate the maximum rated load with an average deceleration of 1 g. Some contexts where these limits have appeared are listed in **Table 4**.

Table 4 Some buffer deceleration limits

Deceleration limit [g]	Source	Author	Year
"Equal to velocity height" = 1.0 g (?)	Passenger Elevators	Brown	1904
64.4 ft/s^2 = 2.0 g	Electric Elevator Equipment for Modern Buildings	Grierson	1924
1 g (average) 2.5 g (maximum)	Der neuzeitliche Aufzug mit Treibscheibenantrieb	Hellborn, Hymans	1927
80.5 ft/s^2 = 2.5 g	Electric Lifts	Phillips	1961
25 m/s^2	NEN 1081 Safety regulations for electric lifts	Nederlands Normalisatie-instituut	1971
1 g (average) 2.5 g (peak)	Der Aufzugbau	Franzen, Englert	1972
9.81 m/s^2 (average) 24.5 m/s^2 (peak)	ASME A17.1/CSA B44	The American Society of Mechanical Engineers	1971 2019
1 g (average) 2.5 g (peak)	EN 81-1 EN 81-20	European Committee for Standardization	1986 2020

Indeed, 2.5 g was regarded as the safety limit for passengers and the 1 g limit was needed to ensure that the deceleration of the descending body matches that of the ascending body. The significance of this can only be understood by reading the earlier ASME paper by Hymans, which highlights the importance of ropes slipping during buffer run to maintain a safe top clearance and the significance of slack hoist rope produced as a result of buffer run.

Parallels can be drawn from here to Donandt's 1963 article "*Die Bremskraft der Fangvorrichtungen von Schnellaufzügen und das Springen der Gegengewichte beim Fangen*" (*The braking force of the safety gear of high-speed elevators and the counterweight jump during gripping*) [20] where he analyses the same phenomenon from the perspective of safety gear engagements. The conclusions concerning counterweight jump have defined the engineering of high-speed lifts to this day.

It is also worthwhile to consider that due to the influence of *Der neuzeitliche Aufzug* the 1 g limit for buffers became the industry practice and, in addition, most likely directly affected the requirement for safety gears [21].

4.6 Standardization of lifts

The subtitle of Hellborn's and Hymans' book is "*Charakterisierung, Theorie, Normung"* (Characterization, theory, standardization) and as the subtitle suggests, one main theme is to explain the impact of traction sheave drives to the standardization of lift design. The section – probably written mostly by Hellborn – explains the "typification", which is the principle of constructing a series of complete products such as motors, controls, safety gears, etc., and the "standardization", which aids the economical selection of individual parts. The topic had already been introduced in Hellborn's 1924 article and in modern terms the approach could even be described as "systems engineering" as the aim is to design efficient lift systems. Overall, the possibilities for standardization were one of the reasons why traction lifts were such a paradigm shift and Hellborn's analysis would merit a much wider treatment than what is possible here.

5 DISCUSSION

Although the traction lift had already existed before the books by Hellborn, Hymans and Donandt were published in 1927, they acted as a catalyst in the major transition within the lift industry, by making the basic dimensioning principles available for a wider audience. The age of drum lifts was decidedly over.

Several of the dimensioning principles introduced in these books have lived on to this day. This was also influenced by the fact that Hymans and Donandt assumed significant positions in the lift industry in later years and were both involved in the development of lift safety standards.

Admittingly, these principles have *stood the test of time*, but it should also be recognized that these old principles should not go unchallenged. Already in 1927 Donandt disagreed with some of the claims made by Hellborn and Hymans, and the evidence to support some of the basic assumptions was not properly presented – at least by scientific criteria. On the other hand, one could also argue that on some points the original wisdom has been misrepresented in later years.

In the century after the books by Hellborn, Hymans and Donandt, the lift industry has faced other paradigm shifts, such as the introduction of machineroomless lifts and coated suspension members. The recent trend towards eliminating or minimizing pit and headroom heights may also become such a game changer – not to mention the impact of digital transition.

As general technology evolves and the requirements change, we must be ready to challenge the old assumptions. But to do that, one must first recognize why certain things have been the way they are. This is why it is so important to go back to the source - and therefore *Der neuzeitliche Aufzug mit Treibscheibenantrieb* and *Über die Berechnung von Treibscheiben im Aufzugbau* are still relevant today.

REFERENCES

[1] F. Hymans and A. V. Hellborn, *Der neuzeitliche Aufzug mit Treibscheibenantrieb,* Berlin: Julius Springer, 1927.

[2] A. V. Hellborn, *Die neuere Entwicklung der Aüfzugsmaschine und die damit in Verbindung stehende Normalisierung*, vol. XVII, Födertechnik und Frachtverkehr, 1924.

[3] H. Donandt, *Über die Berechnung von Treibscheiben im Aufzugbau*, Karlsruhe: Karlsruhe Technical University, 1927.

[4] *Official Gazette of the United States Patent Office*, 1878, p. 134.

[5] G. W. Gibson, *Fred Hymans and Theory of Rope Tration, Part One,* Elevator World, 2017.

[6] G. W. Gibson, *Fred Hymans and Theory of Rope Tration, Part Two,* Elevator World, 2017.

[7] L. E. Gray, *Lift Books 1890-1940,* Northampton, 2014.

[8] O. Joukio, *Sanelua vai vuorovaikutusta?,* Turku: University of Turku, 2015.

[9] *History of Institute for Material Handling and Logistics,* [Online]. Available: https://www.ifl.kit.edu/english/261.php [Accessed 12.03.2022].

[10] E. Bahke, *150 Jahre Lebensdaueruntersuchung von Seildraht und Drahtseil,* Internationales Kolloquium 150 Jahre Drahtseil, Technische Akademie Esslingen 13.-14. September 1984.

[11] *ASME A17.1/CSA B44 Safety Code for Elevators and Escalators,* New York: The American Society of Mechanical Engineers, 2019.

[12] G. Benoit, *Die Drahtseilfrage,* Karlsruhe: Verlag der Hofbuchhandlung Friedrich Gutsch, 1915.

[13] *TRA 003:1981 Berechnung der Triebscheibe,* Verein der Technischen Überwachungsvereine e.V., 1981.

[14] R. Grierson, *Electric Lift Equipment for Modern Buildings*, London: Chapman & Hall, Limited, 1923.

[15] J. Munday, *Some Thoughts on Rope Life,* Northampton, 2017.

[16] O. R. Berner, *Lebensdauer von Stahlseilen beim kombinierten Lauf über Treib- und Ablenkscheiben unterschiedlicher Rillenform,* Stuttgart: Institut Für Födertechnik und Logistik, Stuttgart University, 2011.

[17] G. W. Gibson, *Rope Traction Theory & Practice,* Elevator World Inc., 2009.

[18] J. Kalliomäki, *Jaakko Kalliomäki sheds some light on the provenance,* Elevator World Inc., 2019.

[19] F. Hymans, *The Emergency Stops of the Gearless Traction Elevator at the Terminal Landings,* vol. 48, New York: The American Society of Mechanical Engineers, 1926.

[20] F. Hymans, *Electric Elevators, Book I: Electric Traction Elevators, Elevator Hatchway Equipment,* Scranton, Pennsylvania: International Textbook Company, 1931.

[21] H. Donandt, *Die Bremskraft der Fangvorrichtungen von Schnellaufzügen und das Springen der Gegengewichte beim Fangen,* vol. 4, 1963, pp. 374-380.

[22] A. Leenders, *EN 81 Handbook*, 1986.

BIOGRAPHICAL DETAILS

Jaakko Kalliomäki is currently working as Technical Product Owner of high-rise elevator core technologies at KONE Corporation. He has a master’s degree in Mechanical Engineering from Helsinki University of Technology and 15 years of experience is high-rise lift engineering. His expertise areas include Systems engineering, hoisting dimensioning, seismic lift design and building sway. He is also a keen lift history enthusiast.

Component Based Modular Elevator

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Keywords: Lift**,** Elevator, Modular, Ready-made, In Stock, Components, Segments, Smart, 3D/Parametric design

Abstract. This paper addresses a "Component-based Modular Elevator" (CBME) design. The idea is to have readily available components (mechanical, electrical & electronic) of an elevator ideally in a local warehouse, that are totally modular in nature, easily configurable to build one entire elevator system. This method facilitates easy procurement, deployment, and installation of the elevator without a need of placing an order with the manufacturing plants (OEM)/ logistics centers.

The elevator industry supply chain includes all the processes involved in ordering, producing, shipping, and other logistics delivering to the construction sites. The local selling companies do not have manufacturing plants but import the materials from their principal factories' world over (mainly from China & Europe).

Modular design is a method of breaking down a system into smaller sections/modules that can be constructed individually and then combined to form a larger system. From less customization and design flexibility, modularity also has advantages, such as augmentation (modernization). The design aims to combine the benefits of standardization (low manufacturing costs) and customization.

Traditionally built elevators still need to be manufactured as per specifications, even if they are standard models. Whereas, from a segmented modular elevator design, different models of elevators could be built up using segments that can add up to have different capacity elevators using prefabricated elevator modular mechanical & electrical components. The concept of modular elevator design was always present, but not at the component level. The advantage we can gain from such a design is that the parts can be pre-ordered (or 3D printed), stocked, and these can be assembled at the job site to suit the specification.

A methodology proposing CBME essentially takes a specific modular design of major components of an elevator application as an example to show the development of a fully modular elevator.

1 INTRODUCTION

The vertical transportation industry is usually categorized by product (new passenger/freight lifts, escalators, moving walkways), service (installation, modernization, and repair) and market (residential, commercial & industrial). A good vertical transportation system is one of the first aspects of a good building design. Over the past few centuries and particularly in recent decades there has been rapid **urbanization** and the world has witnessed a mass migration of populations from rural to urban areas. More than 4.3 billion people now live in urban areas as per estimates from the UN.

This means over half of the world (55%) live in urban settings. With the world population growing and with the lack of livable area, housing has increased into multi-level units, thus the need for vertical growth and transportation too has been increasing proportionately.

1.1 Growth And Future of World Lift Industry

The global lift and escalator market was valued at USD 79.70 billion in 2021. The market is projected to grow from USD 83.86 billion in 2022 to USD 132.08 billion by 2029, exhibiting a CAGR of 6.7% during the forecast period. The global COVID-19 pandemic has been unprecedented, with lower than anticipated demand across all countries compared to pre-pandemic levels. Based on the analysis, the global market had exhibited a decline of 3.5% in 2020 as compared to 2019.[1]

Post Covid, the rising investments in commercial and residential infrastructure projects in the developing and developed economies and resumption of construction activities on some of the major projects in several countries are expected to bring in positive results in elevator and escalator market growth. Also, the increasing focus of manufacturers in offering products with improved safety is expected to result in market growth.[1]

2 STRATEGY IN THE ELEVATOR INDUSTRY

The lift industry is currently in the maturity stage if we consider the typical electric traction & hydraulic elevators. However, traditional elevators still experience the growth stage as the companies have been coming up with new features and improvements on these regularly, like the machine room less (MRL) elevators, green technology in the last 2 decades and recently the revolutionary linear motor technology ropeless lifts , carbon fiber ropes, DC battery powered lifts, usage of IoT, smart elevators etc. Every few years, as technological improvements happen, the demand for these starts to rise and then matures as customers start waiting for newer models and better features.

2.1 Strategic Group Map for Elevator Industry

Firms in the same strategic group in the lift industry have two or more competitive characteristics in common, like sell in same price/quality range, be vertically integrated to same degree, have comparable product line breadth, use of identical technological approaches etc. [8]

Although, the groups do not expose big differences in how all the companies in a country /region perform, except for some “other smaller” companies that supply elevators to builders who are very cost conscious. Only Mitsubishi, Otis, Kone, TKE & Schindler compete neck and neck on large projects where brand name, quality, and price matters to the clients.

2.2 Elevator industry and Blue ocean thinking

- ‘Red Oceans’ in elevator industry are already well defined (mid to high rise market) and competition is very high.
- ‘Blue oceans’ are new market spaces where competition is minimized. The innovations in Hybrid or fully battery-operated elevators, LVA (low voltage architecture), and open loop control systems, super high-rise systems, and IoT are future innovations in elevator technology and major brands are working hard towards them. These market spaces are currently intensively explored by all major brands.

However, the concept of modular (ready in stock) lifts is yet to be explored in the elevator product range!

2.3 Elevator Industry’s Critical Success Factors

In the service industry, particularly the volatile, capital-intensive elevator industry, success factors cover a wide spectrum: people, service, product, innovations, revenue/cost control, materials, and financial management. Common types of key success factors of elevator industry:

2.3.1 Technology & innovation driven:

- Product innovation capability (like flat steel belt, battery driven elevator, Carbon fibre ropes and the recent TKE Multi® rope less lifts etc.)

- Expertise in a given technology (Green technologies for CO_2 foot print reduction using VF & regenerative drive systems, compact gearless machines, no lubrication systems, LED lighting, lifts going under standby mode when not utilized etc.)

- Latest using IoT enabled elevators and use artificial intelligence (AI) to enable vertical transportation of passengers and commodities effectively. It is also a process of upgrading the lift in order to handle new technology, perform better, improve safety, and ensure the maintenance is up to date.

2.3.2 Manufacturing driven:

Although a major percentage of the elevators are imported into most of the countries from China, Far East, Europe, Japan, US, India etc., the manufacturing processes will have a direct or indirect impact of the cost & quality of the final products.

There are several factors affecting manufacturing costs: [9]

- Labour Costs – The socio-economic conditions in the area where the activity is done frequently affect labour expenses. Working with suppliers who employ lean manufacturing techniques translates to least amount of waste and greatest quality.

- Raw Materials – Raw materials are commodities that are traded extensively on the global market. With very few exceptions, the cost is determined by the amount of material consumed, so it doesn't really matter where production takes place.

- Part Complexity – Complexity doesn’t always improve a product’s look or performance. In fact, overly complex designs can hinder a product’s utility and performance while being more expensive to make.

- Volume – Raw material suppliers occasionally provide discounts for large purchases; thus, volume is another factor to take into account. This should be taken into account for the course of the product, not just for one particular production run.

- Precision – Repeated accuracy is what is meant by precision which is easily achieved with modular products. It has to do with consistency within a range of allowable deviations from the nominal value. Many product developers are unaware that investing in ever-increasing precision and accuracy leads to cost reductions drastically.

- In country value - For the countries to remain economically sustainable long-term, it is key to ensure the development of its local talent, diversification of its GDP through sourcing more goods and services locally. It means engaging with local stakeholders to hire, buy and invest locally. To achieve this, many Middle East countries have either approached this by specific contractual terms or by an ICV program. Here, a criterion is set to calculate an ICV score for a supplier and that score is used in making procurement decisions.

- Environmental related measures -
    - CO_2 emissions reduction
    - Green production cycle: Selecting all components for optimal performance with the smallest carbon footprint possible.
    - More recycling, less waste, innovative solar system power

2.3.3 Distribution driven

The 1970s to 90s saw many elevator companies being operated by agents and not directly by the foreign principals. But in the late 90s the trend changed, big elevator companies became major shareholding companies operating directly implementing their standard policies and procedures, although there are still many elevator company agents operating. However, the manufacturing facilities are still almost non-existent in most of the countries.

3 THE CHALLENGES IN THE ELEVATOR INDUSTRY

The following are the most common challenges most lift selling companies face:

- Forecast accuracy and unpredictable demand from clients. This is never constant and varies due to a combination of several issues like construction delays, client indecisiveness, delays in approvals etc.

- Client, Main contractor & Consultants general delays and elevator contractor award finalization delays (at times, this happens even during the last stages of construction).

- As a result, demand for the shorter delivery times shall always remain and elevator manufacturers have to gear up for this demand uncertainty at all times. The trend of shorter lead time significantly impacts the project's duration. Developers need to be vigil about the trends in the market and human behaviour.

- Supply chain issues: Supply Chain is a cohesive built-up process and like any other manufacturing supply chain [7]. It comprises of two combined processes such as Production Planning & Inventory Control and Logistics Process as shown below:

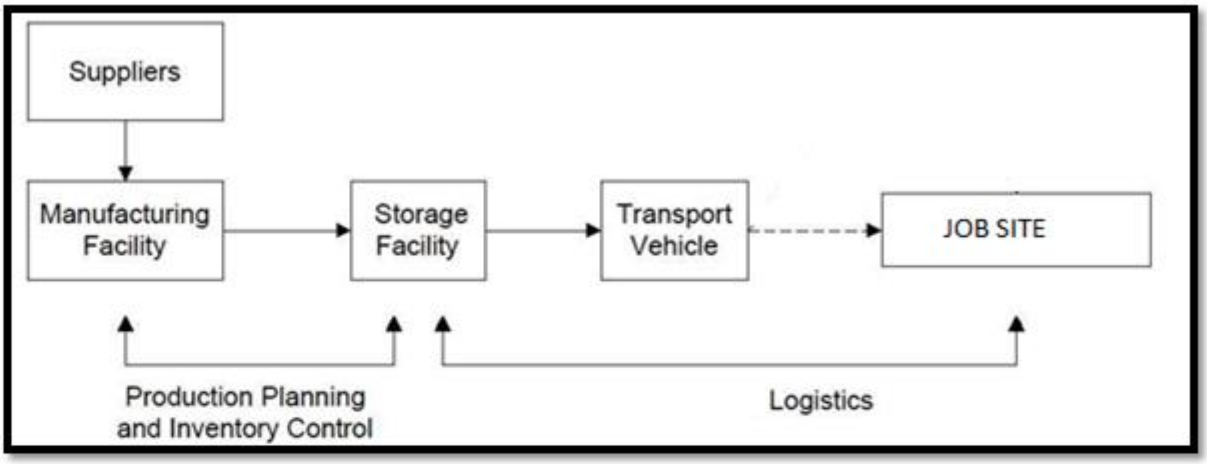

Table 1– Traditional Supply chain management in Elevator Industry

Lift selling companies in most countries do not own their manufacturing plants but import the materials from their principal factories world over. However, with most factories plagued with delayed manufacturing schedules, shipment, and other last mile logistical issues, these very often lead to overall delayed delivery times.

The manufactured goods are usually shipped through several sea ports. This brings a huge challenge to the elevator companies. Blockades at ports during peak seasons like in summer and like in the current pandemic situation in China has created backlogs of thousands of containers with a loss of millions of dollars to businesses.

- Unpredictable demand: This is independent of forecast accuracy issues; unpredictable demands are mainly resulting from project announcements delays and overall market scenarios in real estate/ construction business.

- As a result, the major lift companies tend to lose of lot of market share in the lower segment, where the "other smaller" competitors (and the trading agencies) provide quick deliveries to the clients in urgency. Some have stock of the major components, and they shop around for other parts, procure, assemble and handover to the client in a short time.

A ready in stock elevator or a modular elevator locally would be a perfect solution in such situation, thereby avoiding this entire process of ordering, shipment/logistics management! The current sustainability requirements from authorities demand local procurement as much as possible that necessitate the requirement of a CBME.

1. MODULAR LIFT & METHODOLOGY

As the global elevator industry continues to restructure and consolidate (post Covid), the home base of operations of the major players is becoming increasingly less relevant to the competitive dynamics of the business, with a handful of multinational companies dominating the business in most geographic areas – especially with respect to product manufacturing.

In this extremely challenging market, although the construction industry is moving slow-paced world over, the profit margins in the new equipment (installation) market are badly hit due to the extreme competition. For a strong foothold in the industry, major lift suppliers are continually investing in innovation & RD and aim to bring out new products every three to four years.

More than 60% of the new elevators sold and installed are between the lower end capacities i.e., 320kg to 1000kg that are mostly installed in private homes/villas, apartments & small offices. The idea of an innovative "Modular Segmented Elevator" was mainly within this range of duty loads that is readily available on stock and on a "one size fits all" basis.

Having a modular elevator product ready in stock can reduce this lead time, drastically reduce logistics, installation costs and increase their respective market share by offering ready-to-be-installed elevators by any supplier.

This product should be wholly modular in nature, segmented, ready in stock and available 24/7 with the local elevator selling companies, who do not possess elevator manufacturing facilities in their operating country. This reduces their total dependency of placing orders with the overseas manufactures (OEM/logistics centers) and avoids delays in ordering, manufacturing, shipping, and other usual processes involved. This ultimately might bring the order & manufacturing cycle time to zero (from the current global average 8 weeks manufacturing and 5 weeks shipment).

In the last decade, the concept of modularity has caught the attention of engineers, management researchers and corporate strategists in a number of industries. When a product or process is "modularized," the elements of its design are split up and assigned to modules according to a formal architecture or plan. [3]

A complex system can be easily managed by dividing it into smaller modules and examining each piece separately. Modularity refers to "the degree to which a system's components can be separated and recombined" into new configurations with little loss of functionality). [10]

Several powerful forces are behind modularization:

- the rate of technological change is accelerating,

- customers, empowered by advanced technologies, are demanding greater product variety at lower prices, and

- technology-intensive products are becoming more complex. The potential benefits of modularity include economies of scale, increased feasibility of product/components change, increased product variety and reduced lead time, decoupling tasks and ease of product upgrade, maintenance, repair, and disposal.

The concept of modularity is commanding increasing attention from researchers because of its capability to cope with a turbulent manufacturing environment. One of the key principles that will determine the factory of the future is the modular organization of manufacturing processes, which promises to combine the advantages of standardization and flexibility. [10]

So, a modular system can be characterized by the following:

- Functional partitioning into discrete scalable, reusable modules consisting of isolated, functional elements
- Rigorous use of well-defined modular interfaces
- Ease of change to achieve technology transparency

Besides reduction in cost (due to lesser customization), and flexibility in design, modularity offers other benefits such as augmentation (adding new solutions by merely plugging in a new module).

Modular design is an attempt to combine the advantages of standardization (high volume normally equals low manufacturing costs) with those of customization. A downside to modularity (and this depends on the extent of modularity) is that modular systems are not optimized for performance. This is usually due to the cost of putting up interfaces between modules

3.1 How can modular elevators be an alternative to stick-built elevators?

- *Shorter Lead Time*: A complete, customized elevator can be at the door ready to install in a week's time after drawings are approved. Typical elevators have a 4 to 5 months lead time.

- *Faster Installation*: Elevator installation is one of the most problematic, expensive, and time-consuming aspects of construction. Modular elevators can be stored, ready in stock or transported in a short time and are ready for installation. Installation can be done in the shortest possible time, minimizing disruption at the job site. Stick-built elevators generally take about 3-4 weeks to assemble on-site.

- *High Quality*: Standard elevator parts can be built under controlled factory conditions to meet strict quality and tolerance standards.

- *Lower Cost*: Pre-engineered elevators save time and money as standardization brings down the costs drastically. Unlike conventional elevators, modular elevators allow for more design freedom, increased functional versatility and an uncomplicated solution for buildings that need to adapt or modernize. They can also enable virtually any kind of facility to achieve and/or improve accessibility while saving time and money. A modular elevator can be constructed with high-quality components and be manufactured in a plant-controlled environment, which results in a high-quality product that greatly minimizes design and engineering costs.

- *Safer Construction*: Standardization of the parts reduces the complications of imparting repeated training to the work force, thereby increasing the technical knowhow of the installation and thereby reducing job site safety hazards.

- *No More Imports*: All the required components can be ordered and stocked as per the quarterly forecast planning based on monthly elevator sales & material consumption. Like reorder point planning, forecast-based planning can be operated using historical values and forecast values and future requirements can be determined via an integrated forecasting program.

The forecast, which calculates future monthly requirements using historical data, can be carried out at regular intervals, which are automatically determined, and are continually adapted to suit monthly sales. This however needs a special storage space in a warehouse/spare parts centre. A compact warehouse can be designed to accommodate a space needed for 6 to 8 full elevators as a minimum.

So, whether it's a new or retrofit project, a modular elevator is the ideal vertical transportation solution.

4 HOW MODULAR DESIGN WORKS

The most popular elevator design is the roped elevator (however now ropes are replaced with flat this steel belts coated with polyurethane (Otis) and even carbon fiber ropes (Kone). Roped electric traction elevators are much more versatile than hydraulic elevators, as well as more efficient. Typically, they also have more safety systems. MRL lifts are energy efficient, require less space, and their operation and reliability are on par with gear-less traction elevators.

4.1 Elevator System Components:

Elevator components, features and operation may vary from one elevator to another. So, this raises the complexity of ordering an elevator, as a result each elevator is always considered as a separate unit for order placement.

A standard elevator always includes the following basic components:

- Car (car sling, upright channels, safety, cab, car door, walls, ceiling & COP)
- Hoistway (guide rails, counterweight, suspension ropes/belts, landing doors, position reference systems, buffers etc.)
- Machine & VF drive systems
- Control systems
- Safety systems

4.2 Possible Design Changes To A Standard Elevator To Achieve A Modular Design:

- *Machine:* Compared with the traditional machines, the PM machine has a high efficiency factor, high efficiency, low starting current, large starting torque, smooth running comfort etc. NdFeB (rare earth) magnets are used to excite the rotor which are extremely small in size, light weight, no gear, low noise, and high reliability. These efficiency and installation aspects provide a new solution to building architects in their desire to provide building owners with lower operating costs, while maximizing square footage.

- The permanent magnet industry started to see the beginning of the end of serious rare earth shortages in 2011, as new supplies begin to hit the market during 2013 [4]. With their increasing popularity and as they are becoming an industry standard, the cost of the gearless machines has dropped a lot, and a common machine catering for all the loads from 3 passengers to 13 passengers can be designed easily on a single machine.

- *Controller & Drive:* Lift Control System is the system responsible for coordinating all aspects of elevator service such as travel, speed, and acceleration , deceleration, door opening speed and delay, leveling and hall lantern signals. With the advent of the microchip came significant boosts in elevator-control efficiency. Solid-state control technology, which entered the elevator market approximately 20 years ago, is used on all modern elevator systems. So, with availability of modern controllers & drives, a common controller to cater for all the capacities from at least 3 passengers to 13 passengers can be designed easily on a single controller.

- *Elevators rails:* These elevator guide rails are usually used for vertical lifts & elevators to slide up and down safely and smoothly. With high quality available at reasonable prices in China/Europe, guide rails can be obtained at competitive prices.

- *Elevators platforms, slings, uprights & cab:* These form an extremely important part of a modular design elevator. Elevator slings & uprights are mostly of similar structure & dimensions, so just by having these, slings, platforms, and cab panel steel members designed in a well-designed modular structure, they can be assembled to have any dimension of platform and cabs of various standard sizes suitable for a range of elevator capacities.

- *Cab Interiors:* The interiors provide an innovative way to upgrade the visual appearance of any elevator cab. A cab can have many design options. We can have a range of finishes that can include durable plastic laminates, stainless steel, granite, and wood paneling. Interlocking panels stack one on top of the other, making them a snap to install and can be made even easier to replace in the future. Provisions for Toe kick, handrails, and pad hooks can come pre-installed on panels.

- Likewise, every other component of the elevator can be segmented and have a modular design, so when built with segments, different capacities of elevators can be built.

- *Storage:* The storage of these modular components & materials can be easily held in Stacking Racks. Stackable racking system is the most preferred racking system in warehouse storage system since high storage density racking is achieved in the warehouse in terms of cubic storage area of the modular warehouse. Modular stacking racks racking system is even implemented for storage of long items.

- *Use of 3D printing /Parametric Design*: Parameterization allows designers to create models that are flexible and can be changed regularly. All the models made with the help of digital tools like 3D modeling have certain features. They are described by measures such as length, width, depth, orientation, and geometry. The design is based on the relationship between features, parts, and drawings, and it is powered by imagination.

The futuristic 3D/Parametric design also allows a number of benefits:

- **Flexibility –** Using parameterization in design helps to customize work easily. Product creators can build various design iterations and produce many prototypes.
- **Repeatability** – Parametric design techniques provide the opportunity to use parts of previous projects more than once. In addition, they enable split objects into components and try multiple variations.
- **Time-efficiency -**3D printing helps to save time and budget resources instead of using them to acquire machines for manufacture.

5 CONCLUSION

Today's manufacturing organizations are successful if they accurately anticipate market trends and quickly respond to changing customer needs, with innovative products and improved manufacturing processes. Modularity practices (modular products, processes, and organizational architectures) have long been talked about as effective means to cope with demand uncertainty). Since supply chains compete with one another in today's global markets, it would be useful to empirically explore the true influence of modularity-based manufacturing practices on a supply chain's ability to be responsive [10]

The design analysis of a modular elevator has to be better researched in detail by the R&D professionals in the lift industry. R&D should also play a big role not only on the software aspects of the design side but also bring in advanced technological changes in the mechanical components and create robust systems that form the basis for developing a fully modular elevator.

Often, experts are fearful about introducing a new product and costs if that does not involve new age software & IoT technologies in these times. The main hurdle is getting past the "How much does it cost?" and “Are they really needed”? phase.

The engineering and construction sector has been seeing gigantic advancements in building systems & processes, with availability of digital solutions, and the introduction of modular construction. The concept of modularity is also rapidly catching up with other building systems like MEP, HVAC etc.

Modular elevators, if introduced in the market, can bring about a major increase in the market share of the residential elevators and improve the new sales performance of any selling company at least by 10-15%. This will not only improve the sales revenue but also add value to new sales departments' efficiency, enhanced quality, and improved collaboration while satisfying its most important aspect: to help reduce overall operational costs. Once introduced, a modular elevator would see a significant difference in the sales operations, bookings and generate increased revenue to the organization.

REFERENCES

[1] Fortune Business Insights (industry-reports/elevator-and-escalator-market-100301) (2022)

[2] Ren, Atout et al (2008), *Root cause of construction delays in Dubai*

[3] Baldwin, Clark, (2004), *Modularity in the Design of Complex Engineering*

[4] Walter T. Benecki, (2012), *Permanent Magnet Industry Outlook*

[5] Arthur D. Little, (2005), *Innovation Excellence*

[6] Asme.org, (2013), *Energy Efficient Elevator Technologies*

[7] Chopra, S., and Meindl, P. (2010), *Supply Chain Management: Strategy, Planning and Operation*.

[8] Kotler, P. & Keller, K. 14th Edition (2012), *Marketing Management*

[9] Chris Williams | *Manufacturing Services-Controlling The 6 Factors That Affect Manufacturing Costs*

[10] Ashish A. Thatte, Ph.D., Gonzaga University, *USA Supply Chain Responsiveness Through Modularity Based Manufacturing Practices: An Exploratory Study*

BIOGRAPHICAL DETAILS

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Dynamic Simulations for Lift Door Health Diagnosis

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Keywords: system simulation, lift, lift door, fault analysis

Abstract. System level simulations enables new possibilities to perform fault analysis of lift door systems to recognize root causes and malfunction indicators linked to the most critical failures. The simulation method utilized for the approach is object-oriented modelling where elements from all areas of engineering are connected to each other as building blocks. Elements such as controller, belt transmission and door mechanics are interconnected forming a complex system representing physical lift door systems. The approach provides explicit outputs of each included element of simulated systems in time domain. In this paper, the outputs of door drive system are described in more detail, including motor encoder data and torque output. Multiple malfunction simulations have been computed and validated with data acquired from physical counterparts of the simulated lift door system. The validation results have proved the credibility of simulations and demonstrated new opportunities to utilize the simulations for developing fault diagnostics.

1 INTRODUCTION

Increasing urbanization have led to higher utilization of lift systems and increased importance of reliability of lift systems. Kaariaho stated that lift doors have the highest call out rate from all lift system components [1]. Thus, by optimizing condition monitoring capabilities for lift doors, maintenance process for entire lift systems is improved.

The challenge is that the condition monitoring optimization requires data from faulty lift doors as the most of doors are functioning correctly. It is also unlikely for lift door systems to have isolated cases of individual malfunctions which is required to identify distinguishable fault related indicators. Furthermore, data collection, analysis and labelling are done with back reports which as a process has potential for improvement.

In this paper, a solution of using system level simulations to provide synthetic data for training machine learning (ML) models for condition monitoring of lift doors is presented. The method of providing synthetic data using simulations have been proven as an efficient method for improving ML algorithms as discussed in paper by Klein and Bergmann [2]. The simulations can provide data from lift door systems with individual malfunction cases which from the fault identification patterns can be isolated.

The lift door simulations model presented in this paper have been validated and discussed in a Masters thesis [3].

2 SIMULATION METHOD

Lift simulations targeted different aspects of door performance and design optimization. The studies are primarily conducted by analyzing the system from static perspective. In this paper the focus is on dynamic simulations, since they are the most effective in capturing indicators and root causes of underlying lift door related malfunctions. Dynamics of the lift doors must be captured to detect the subtle changes in the system before failure modes linked to studied malfunction cases occur during operation cycles.

The lift door model described in this paper has been created using object-oriented modelling method. In this method, different components from various fields of engineering are modelled as building blocks which are interconnected to each other forming the complex mechatronic system as demonstrated in Figure 1. Equations are formulated and calculated based on these building blocks and interconnections during simulation computations. [4] The quantities of system variables are solved explicitly in non-linear timesteps which is available as output data.

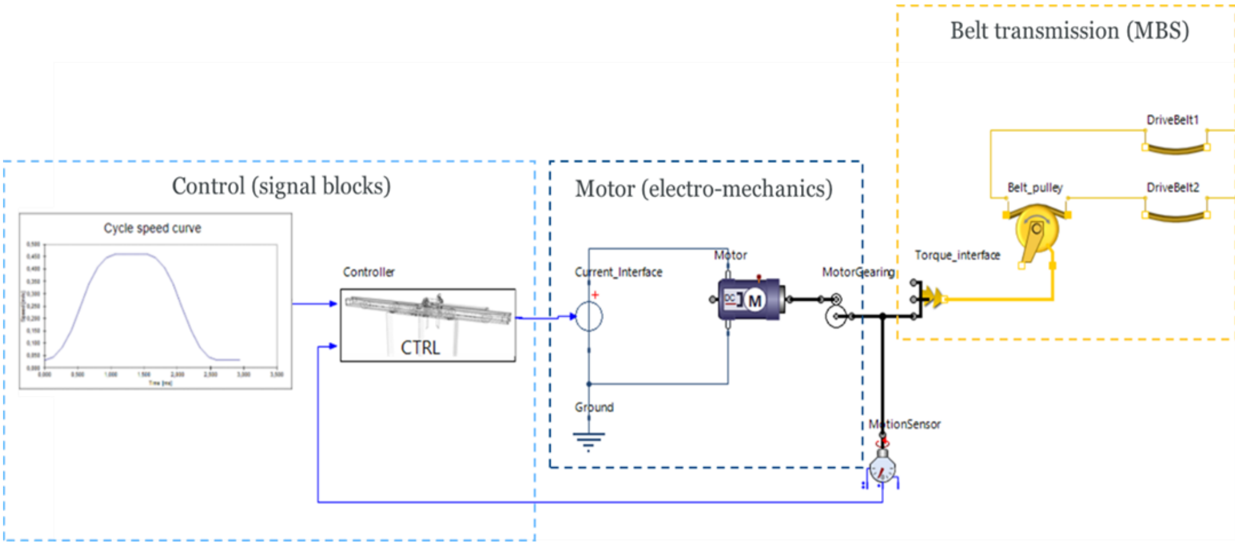

Figure 1. A belt drive system created with SimulationX

A major benefit of using the modular object-oriented modelling is the efficiency the method brings in altering between various configurations of lift systems which are simulated. Modular building blocks representing components of lift door system can be replaced, changed, and reparametrized. These variations can be for instance, lift door panel type, lift door dimensions, speed settings, coupling mechanism. Another benefit of the method is the possibility to include parts from all fields of mechatronic in a single model. By combining all fields of engineering in a system, risks of miscommunications or misconception between cross-discipline experts and engineers are reduced.

Failures of lift door related malfunctions are known to occur in system level. Therefore, cross discipline computation is required in order to include all major factors linked to the lift door malfunctions in simulations. The system level simulations enable high precision simulations with low computational time. However, the challenge for the method is the model simplification definitions. To capture the studied phenomena, contributing components and their interactions must be identified.

3 DOOR MODEL

A two-panel side opening lift door model has been created with a multi-physics software called SimulationX. The software consists of libraries containing elements of mechanics, electronics, and signal processing which have been utilized in the lift door model. (Figure 2)

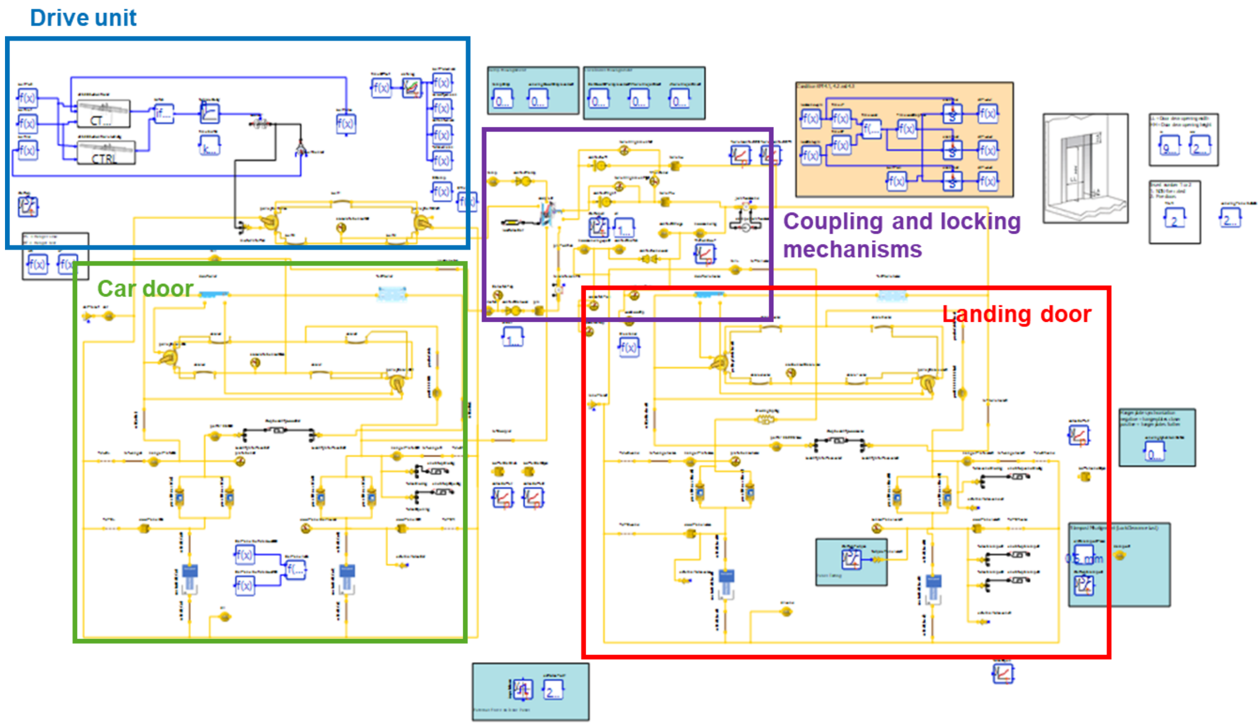

Figure 2. The architecture of lift door model

3.1 Mechanics

As described in the thesis related to the lift door model, mechanics of the model have been built from elements from multibody dynamics in SimulationX library [3]. The mechanical components have been modelled as rigid bodies which have been connected to each other via kinematic joints and various force elements. Elasticity in main contributing components have been simplified by connecting the rigid bodies with spring-damper force elements as demonstrated in Figure 3.

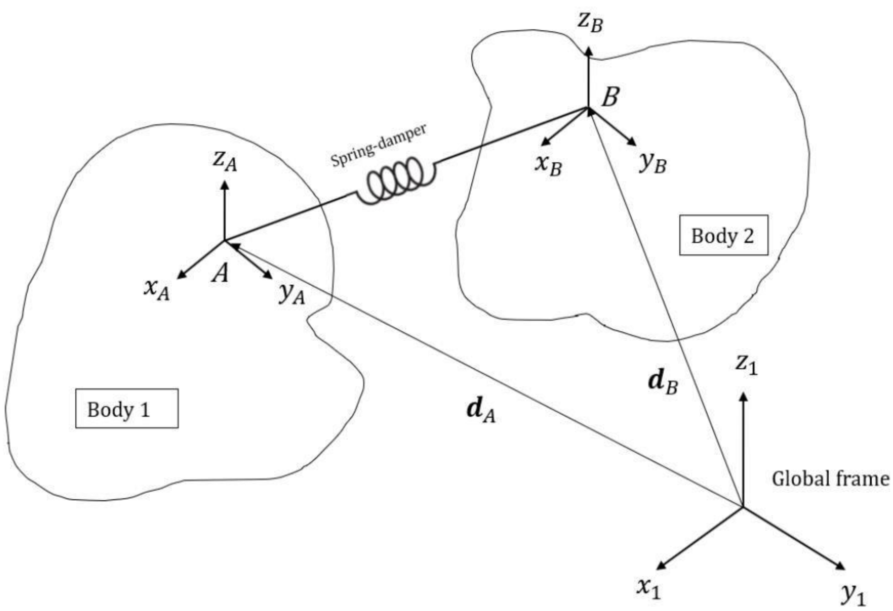

Figure 3. Creating elastic connections between rigid bodies. [3]

For each rigid body, mass, centre of gravity, inertia tensor, position and orientations must be defined from component documentations or 3D-models. The stiffness of elastic material, connections and contacts are defined from analytical methods or laboratory tests.

3.2 Control and electronics

Lift door drive systems operates with closed-loop feedback control as demonstrated in Figure 4. The controllers operate in principle of proportional-integral control mechanism. [3]

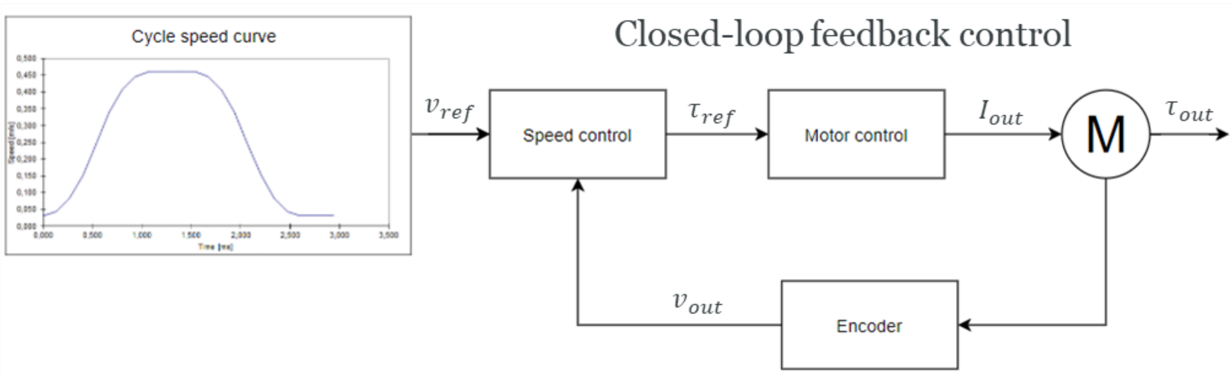

Figure 4. Door drive control loop. [3]

Reference speed curves for door drive cycles are generated inside the model which are defined by lift door speed profile standards which states four speed settings for the two-panel side opening doors. In the model, the motor is modelled as an external torque element connected to the belt transmission. This torque output element is then controlled by the control loop. A detailed motor architecture can be added in the model for studying drive system related malfunctions.

3.3 Outputs

Dynamic response of each element included in the lift door model can be saved and utilized for malfunction studies. Since the end goal of the malfunction analysis is to detect malfunction related indicators, data which are measurable in lift door systems have been selected as outputs for the simulations. Outputs available in lift door systems are door motor current intake and angular position. Other variables utilized for malfunction analysis such as belt position and belt force have been calculated from the lift door motor outputs. These variables have been collected from test lift doors for the validation comparisons displayed in the results section.

4 RESULTS

The simulation results of normal and faulty run for standard lift door cycles are presented in this paper. The faults focused on this paper are related to the issues occurring in lift door locking mechanisms which are safety mechanism for ensuring that lift doors are only opened when the doors are operated. Lift door lock related failures leads to situations where lift doors are stuck which may cause passenger to be trapped inside the lifts. Therefore, it is beneficial to prevent lock related faults occurring to improve lift door reliability, availability, and customer satisfaction.

The normal runs were simulated first to validate applicability of the lift door model used for the fault analysis. The procedure for validation was done by measuring the lift door data from test doors for standard door cycles and comparing the measured data with the simulation data from the identical drive cycles. Results of validation comparison for a normal door cycle are presented in Figure 5. Validation comparison shows deviance at the end of the door cycle because the simulated lift door drive was not programmed to hold doors close in close end force as the feature was not required for the malfunction analysis done in the study which is related to the first section of the door cycle. After the validation comparison for normal runs passes acceptance criteria set for the fault analysis, the validated model can be further utilized in malfunction simulations.

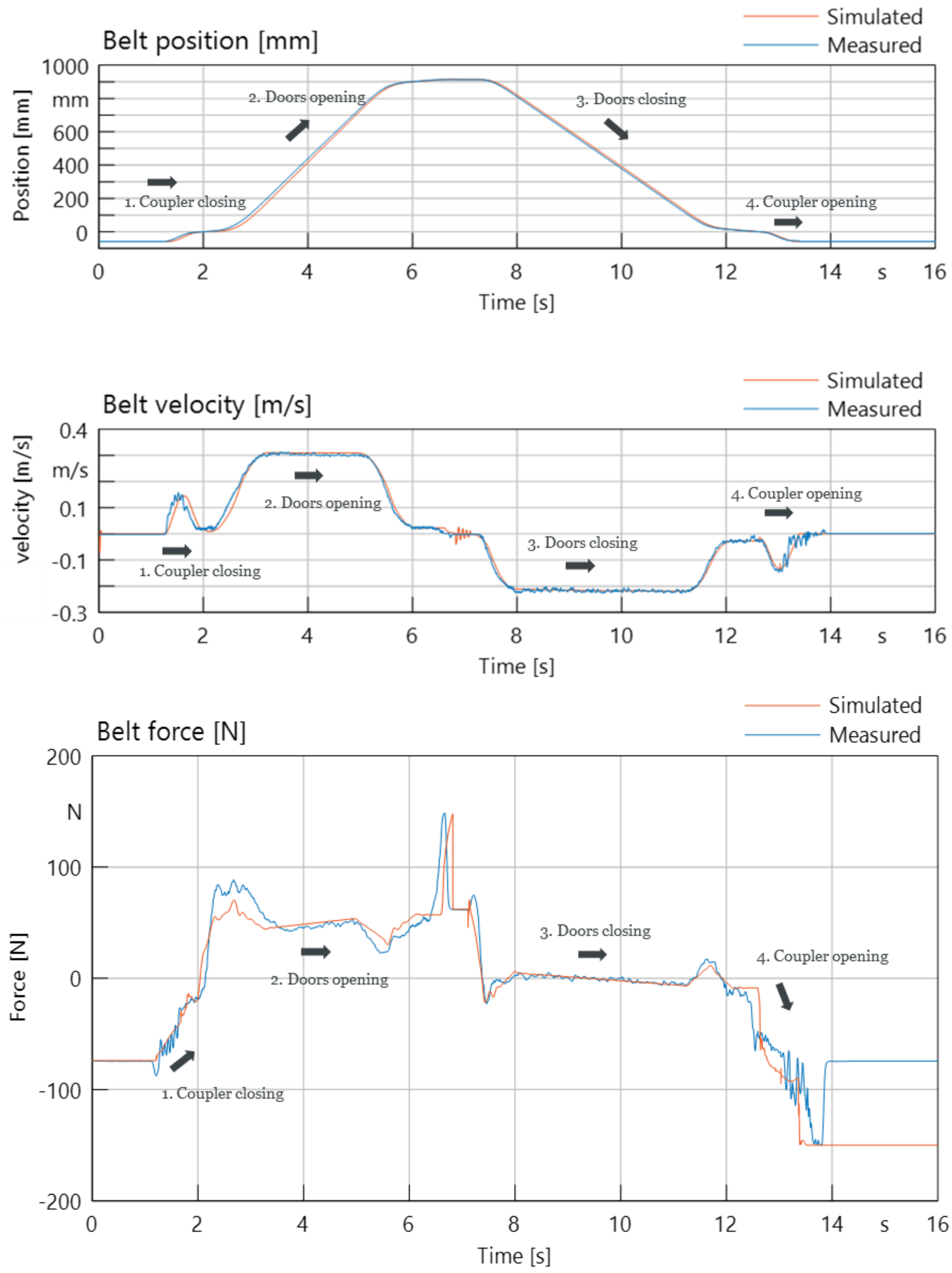

Figure 5. Validation comparisons for normal lift door cycles.

The malfunction simulations are performed by progressively impairing the simulated system to slowly approach the failure mode of the studied fault. For instance, the lift door lock related fault is known to be caused by diminishing lock clearance between lock hook and the counterpart of the lock hook. As displayed in Figure 6, malfunction simulations have been performed by removing lock clearance each simulated door cycle. Then by analyzing the simulation results, the pattern indicating lift lock jamming have been identified from the data. In this case, the jamming lock caused a surge in torque demand during lock opening which can be seen as belt force spike in the outputs.

Subsequently, the identified pattern is validated with laboratory tests by conducting the same cycles with test doors as computed in simulations. In the lock jamming tests, the lock clearance was decreased progressively over multiple door cycles. During each cycle, the motor outputs were measured. The test data is then compared with the simulated data to validate if the signature patterns for the studied case repeats in the measured data as demonstrated in the Figure 6.

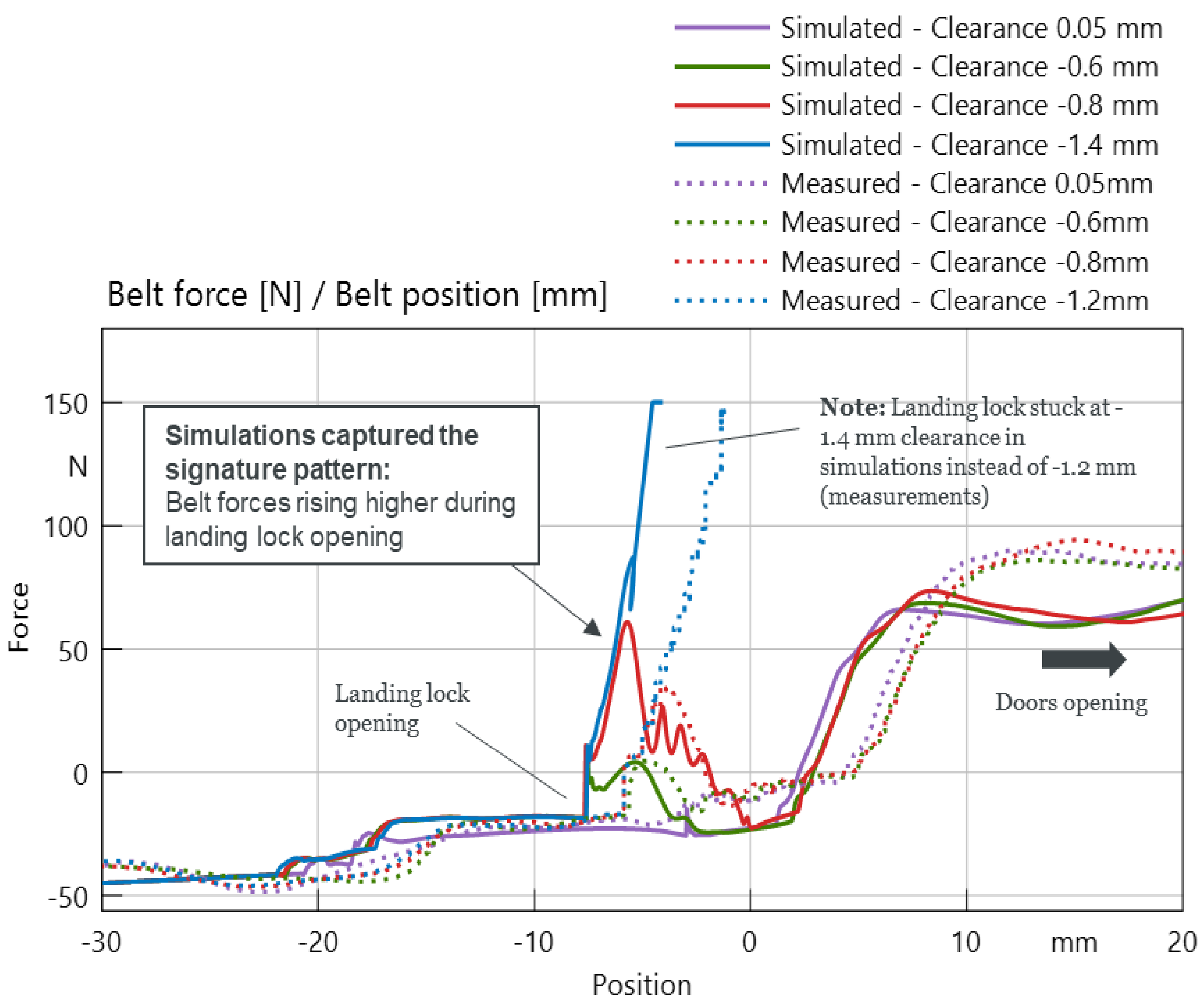

Figure 6. Identified malfunction pattern for lift door lock jamming. [3]

Conclusion

In this paper, simulation method and use cases for system level object-oriented simulation for lift systems have been presented. The lift door system presented in this paper was successfully validated for normal runs and the selected malfunction case. The simulation results correlated well with the measured outputs from test doors and capture the malfunction related pattern.

The validation results proved the capability of the simulations to be utilized for developing maintenance process of lift doors. By identifying the patterns leading to failure modes, thresholds can be set for condition monitoring algorithms in order to flag potential malfunctions in monitored systems. In addition, the faults with validated distinguishable identification patterns from either simulations or measurements can be labelled and utilized as training data for machine learning algorithms.

REFERENCES

[1] Kaariaho, Iiro-Elias. "Testing of elevator door sill assembly.", Bachelor’s thesis, bachelors, Savonia University of Applied Sciences, Finland, 2018.

[2] P. Klein and R. Bergmann, “Data Generation with a Physical Model to Support Machine Learning Research for Predictive Maintenance”, Business Information System II, University of Trier Germany, ISSN 2191-5652, Springer series, 2018.

[3] M. Lin, “Physics-based simulations of elevator door systems”, Master’s thesis, Aalto University, Finland, 2021.

[4] SimulationX [https://www.esi-group.com/products/system-simulation], 2022.

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Investigation into the Closing Force of Passenger/Goods Lift Automatic Power Operated Doors and Recommendations to Reduce the Risk of Injury to Lift Users

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Keywords: Lift, doors, closing force.

Abstract. Passenger lifts are primarily configured with automatic power operated doors to increase passenger flow efficiency. Injuries caused by impact and entrapment between closing powered lift doors do occur, even though safety devices are fitted which should prevent this happening [1]. There are different types of non-contact safety devices that should reverse a closing door to prevent impacts and entrapments. Innovation in technology has allowed these devices to become more effective. However, the devices still do not eliminate entrapment risks entirely. Additionally, many lifts still employ outdated and inferior devices because within the United Kingdom upgrades to improve safety are not mandatory.

1 INTRODUCTION

With lifts conforming to EN 81-20:2020, risks of entrapments between the closing door still exist due to the non-contact device's narrow infra-red beam. The purpose of which, in accordance with EN 81-20, is still to only detect in the event of a person crossing the entrance during the door closing movement [2]. Within the UK between 2002 and 2010, 266 people had been injured in lift related accidents, with the most common injuries sustained as the doors are closing [1].

A final measure of safety to prevent crushing injuries to passengers is limiting the closing force applied by the door operator. This should be less than 147 or 150 Newtons (N) in accordance with the relevant design standard at the time of installation. (It is also noted that closing forces could vary depending on other door safety features in accordance with BS 2655-1). 150 N is a pragmatic limit. This maximum force, however, is stipulated to prevent injury to lift users and is now a widely accepted figure which is laid down in standards and guidance worldwide to limit the risk of crushing injuries.

Unfortunately, automatic power operated door closing forces may not be routinely tested enough to ensure that forces are below the stipulated limit. There is a consensus that many lifts are in service which exceed the closing force limit due to a lack of routine testing. This project set out to understand if these concerns are valid and to seek areas of improvements for the safety of lift automatic power operated doors.

2 FIELD TESTING RESULTS FROM IN-SERVICE LIFTS

An analysis was completed using data from 48 in-service lifts. This provided 384 closing force measurements in total from different measurement positions. The two measurement positions were: top and bottom of the car door and top and bottom of the landing door. These measurements were taken at the ground floor and one other floor. The measurement positions at one landing are shown in Figure 1. A calibrated, spring-type force gauge with a range of 0 N to 159 N was used to measure the lift door closing forces. It is clear from the data obtained that there are lifts in service with closing forces exceeding stipulated limits. 27% of lift doors applied forces exceeding 150 N at one or more of the test positions. The following paragraphs show trends established during the analysis.

Figure 1: Image of landing and lift car doors showing measurement positions

2.1 Differences of measurement position on the same door

55% of doors have force measurements differing between the top and the bottom. The measured closing force was greater at the top on 91% of these doors. Two conclusions can be drawn from the data. Firstly, the measured closing force of doors does differ depending on the vertical position of measurement. Secondly, where these forces differ between the two measurement positions, peak force in most cases is at the top of the door. This is also confirmed by the average closing forces shown in Table 1. The reason is suspected to be due to mechanical losses when measured further away from the door gear.

Table 1: Average forces comparing different measurement positions

Measurement Position	Average Closing Force (N)
Ground floor - Car door - Top of door Ground floor - Car door - Bottom of door	106.1 101.6
Ground floor - Landing door - Top of door Ground floor - Landing door - Bottom of door	105.4 102.7
Top floor - Car door - Top of door Top floor - Car door - Bottom of door	109.8 103.5
Top floor - Landing door - Top of door Top floor - Landing door - Bottom of door	108.1 103.4

2.2 Differences between landings

59% of the tests have closing force measurements differing between landings. 60% of the measurements are greater at the upper landing where the discrepancies are identified. To confirm this, average measured closing forces are higher at the top floor at every comparison as shown in Table 2. Most lifts that were tested featured sprung landing door self-closing devices. Therefore, this difference is suspected to be due to the often-increased use of the ground floor and therefore strain to the spring resulting in reduced self-closing forces.

Table 2: Average forces comparing differences between landings

Measurement Position	Average Closing Force (N)
Top floor - Car door - Top of door Ground floor - Car door - Top of door	109.8 106.1
Top floor - Car door - Bottom of door Ground floor - Car door - Bottom of door	103.5 101.6
Top floor - Landing door - Top of door Ground floor - Landing door - Top of door	108.1 105.4
Top floor - Landing door - Bottom of door Ground floor - Landing door - Bottom of door	103.4 102.7

2.3 Differences between car and landing door

Measured closing forces are the same on 46% of the doors. Where differences of force are identified between the car door and landing door, the position of the highest force is split 53% and 46% respectively. Average closing forces are compared in Table 3. The difference of closing forces between the landing door and car door is negligible and suggests efficient coupling between the landing and car door.

Table 3: Average forces comparing car door and landing door differences

Measurement Position	Average Closing Force (N)
Ground floor - Car door - Top of door Ground floor - Landing door - Top of door	106.1 105.4
Ground floor - Car door - Bottom of door Ground floor - Landing door - Bottom of door	101.6 102.7
Top floor - Car door - Top of door Top floor - Landing door - Top of door	109.8 108.1
Top floor - Car door - Bottom of door Top floor - Landing door - Bottom of door	103.5 103.4

2.4 Differences between door drive types (linear and harmonic)

17% of lifts tested utilised harmonic door operators. 50% of the harmonic systems applied a closing force over 150 N and 88% exerted over 100 N. When compared to linear systems the figures are 23% and 48% respectively. The average measured closing force of harmonic operators is 123 N and for linear operators is 102 N. It is reasonable to state that harmonic door operators are likely to apply a greater closing force to lift doors when compared to systems utilising linear door operators. This is suspected to be due to the increased ease of adjustability of linear operators. Figure 2 shows the recorded differences.

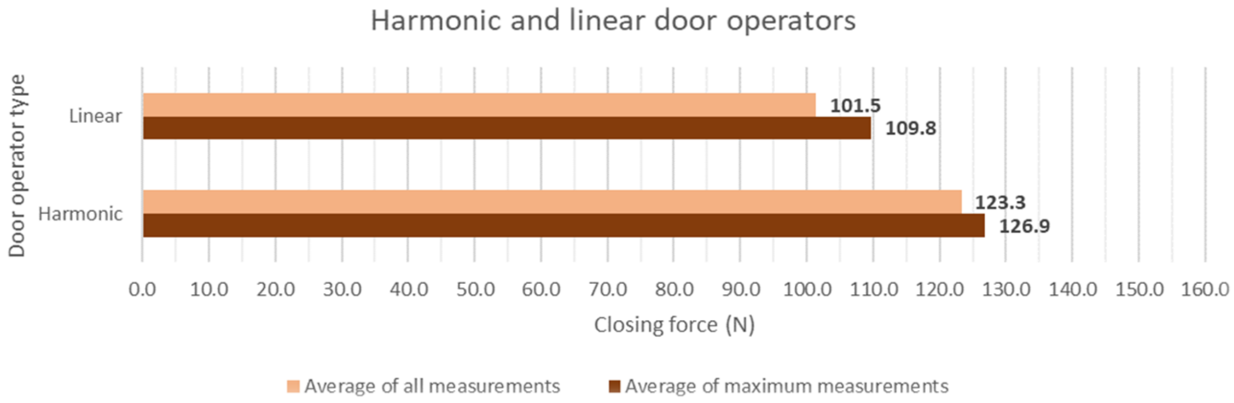

Figure 2: Chart comparing linear and harmonic car door operators

2.5 Differences between side and centre opening doors

69% / 31% of lifts tested featured side and centre opening doors respectively. Table 4 shows the average forces of the comparable doors. Harmonic door operators are not included within this comparison because they are mainly coupled with side opening doors within the data, and the type of door operator appears to have the greatest influence on forces as discussed in paragraph 2.4. For those with just linear door operators, it is evident that when configured with side opening doors higher closing forces are applied than with centre opening doors. 21% of centre opening doors applied a closing force of over 150 N compared to 26% of side doors. It is reasonable to confirm that lifts configured with side opening doors are generally set with higher closing forces.

Table 4: Average forces comparing side and centre opening doors

Door opening	Average Measured closing force (N)
Side	109.5
Centre	89.7

3. COMPARABLE POWERED AUTOMATIC DOOR SYSTEMS

Having established safety measures utilised with automatic power operated doors fitted to passenger lifts, it is prudent to investigate other powered door systems in seek of further potential safety improvements. Comparison with other door systems does identify additional measures that could be adopted to further improve lift safety by reducing door entrapment risks.

3.1 Train bodyside doors

Power operated doors fitted to trains are similar in principle to those fitted to passenger lifts. With trains, traction power should be inhibited until all bodyside doors are closed and locked. EN 14752:2019 is an 88-page document detailing the safety of bodyside entrances fitted to trains. This compares to 15 pages detailing lift door safety within EN 81-20:2020. Revisions of EN 14752 were published in 2005, 2015, 2019. Amendments to the 2019 document are also available for public review. This demonstrates that improvements to train bodyside doors are actively identified, quickly implemented and therefore safety is continually improved. Comparably, text on lift power operated doors from BS 2655:1970 remains largely unchanged within EN 81-20:2020.

The most basic safety measure used on train bodyside doors, that is not applied to passenger lift power operated doors, is the application of entrapment warning signs. These stickers are fitted to train doors and highlights danger to passengers.

There are some common safety measures shared between the two applications, such as non-contact safety devices which are already discussed. However, train bodyside doors include additional safety features. Some are detailed below:

- Automatic door closing is only enabled when there is nobody in the door portal for a specified time. The door portal is a specified area.
- There must be an audible signal that the doors are about to close, which is standardised to a specific pulse and frequency.
- There must be a visual indication both inside and outside of the train warning that the door is about to close.
- The door control system must contain loops to stabilise forces.
- Detection of obstructions must occur in less than one second.

3.2 Powered retail doors

Retail doors are perhaps the most utilised power operated door within the UK. Facilities usually leave the pedestrian no other option but to enter through the powered door. Risks presented due to high foot-flow through these types of doors are recognised within BS 7036-1, which stipulates that operational safety checks should be conducted periodically by the property occupier. For shops, hospitals and airport settings, these checks should be carried out at least weekly [4]. It is stated that the checks must include operational tests of safety devices and non-contact systems should be tested in accordance with BS 7036-2 [5].

In addition, BS EN 16005 also stipulates that tests of door closing forces 'shall be carried out in the worst conditions and configuration'. Included are locations of where to measure forces [6]. Daily or weekly checks are sometimes carried out on lifts by building occupiers, but this is often just to check that the machine is in service, possibly alongside a test of the in-car alarm/communication system.

Powered retail doors must also display 'keep clear' and 'automatic door' signs to give users advance warning of operation and inform them to keep away from the space where the power operated door travels in accordance with BS7036-0.

4 RECOMMENDATIONS

Simple procedures can be implemented by lift duty holders to improve the safety of lift automatic power operated doors. Building occupiers may carry out daily or weekly checks of the lift, but this is likely to just ensure that the lift is in service, possibly with a check of the car alarm and emergency communication system. It is recommended that checks to the lift doors and their non-contact safety devices are also carried out concurrently, or at intervals recommended by findings from a risk assessment. The checks would not be onerous, but should include a physical check of all landing doors with an operational check of the non-contact safety device. This would be similar to checks required on powered retail doors in accordance with BS 7036-1.

The operation of lift automatic power operated doors has specific risks to the safety of lift passengers. Passengers are either not aware of this or have become accustomed to the risk, possibly because lift use is now largely a necessity within daily life. It is common to witness lift passengers stalling a closing lift door by hand to prevent lift car departure, whether for themselves or to assist other lift passengers. Serious injuries and fatalities have occurred on rail networks due to similar entrapment scenarios. To detract against this practice and to protect train users, warning signs must now be placed at the train bodyside door which highlight the entrapment risk. It is recommended that a similar sign is also applied to lift doors. This would be a simple, cost-effective safety improvement which can be made by the lift duty holder to deter lift users from the practice of stalling closing lift doors by hand.

Improvements to the safety of lift automatic power operated doors can be made to the current design standard, EN 81-20. Progress towards safer lift automatic power operated door systems can be made when compared to the safety of train bodyside doors. EN 14752 contains safety features of train bodyside doors that could be adapted for use with passenger lifts. It is recommended that a review is undertaken to assess the feasibility of these as additional safety measures by BSI.

Modern non-contact safety devices fitted to passenger lifts consist of a narrow beam array fitted to the car door only. This offers limited protection to lift passengers as shown in Figure 3. Fitment of 'light curtain' non-contact safety devices to all landings, in addition to the lift car door as shown in Figure 4 would provide protection against the entire potential entrapment area. This would also protect against door opening entrapments, which is another risk not investigated during this project. It is understood that this would however involve major re-working of surrounding architrave at each landing for existing lifts, but could be incorporated into the design of new installations. The diameter of detected objects should also be reduced from 50 mm (EN 81-20:2020) to a measurement that would detect fingers of children and include the entirety of the closing doorway until the doors are fully closed.

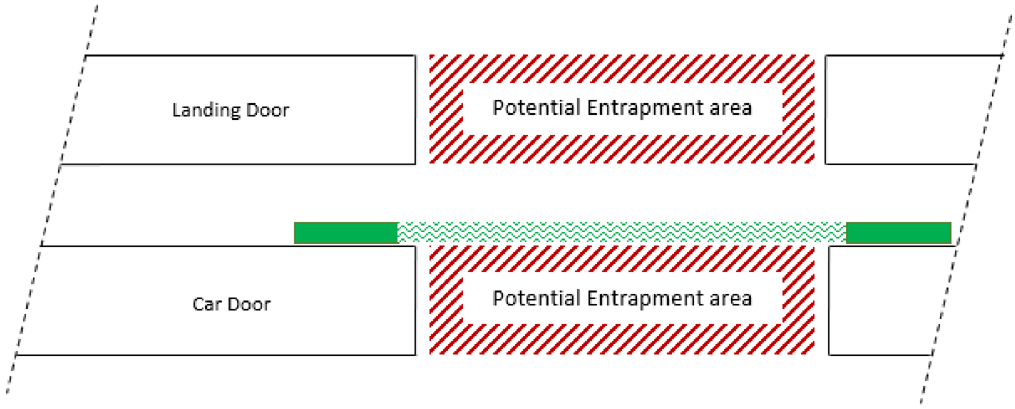

Figure 3: Overhead view diagram of lift door 'light curtain' with common mounting position (indicated green)

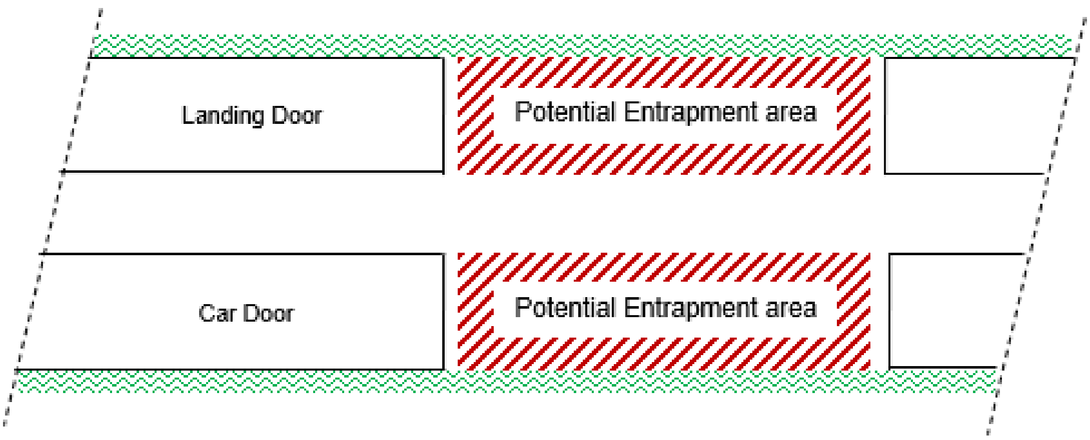

Figure 4: Proposed improvement to door 'light curtain' locations (indicated green)

Passive infrared (PIR) technology could be utilised to better protect entrapment areas of existing lifts. PIR light curtains utilise a single unit and are commonly used within security systems as shown in Figure 5. This technology could be adapted for use at lift landings and due to a single unit, may be a suitable modification to existing lifts because the upgrade would be less intrusive.

Figure 5 PIR intruder detection device [8]

Field investigation has provided data confirming that lifts fitted with automatic power operated doors are in service with door closing forces exceeding stipulated limits. It is strongly recommended that lift automatic power operated door closing forces are routinely checked by the competent person and maintenance personnel.

This investigation has established that a measurement should be taken from the top of the door, at what is assessed to be the least utilised landing. Closing force measurements should also be recorded where there is a change of lift door design between landings, such as foyers of large or extravagant buildings and following replacement of door components.

Closing forces are a protective measure [7] and 150 N is a maximum limit, not a target. It is recommended that lift duty holders carry out a risk assessment with the aim of setting door closing forces as low as possible depending on risk assessment findings. Considerations should include the environment of the lift and the demographic of passengers using the lift.

5 CONCLUSION

Acquiring closing force measurements of automatic power operated doors fitted to in-service lifts has facilitated a better understanding of a problem, whereby force limits exceed stipulated maximum figures. Analysis confirms that many lifts are in service with forces exceeding these limits. Evidence within this paper highlights the requirement for remedial action to reduce or mitigate the risk of impact and entrapment injuries to lift passengers caused by closing automatic power operated doors. Inspection bodies and maintenance providers who assess the safety of lifts should be measuring closing forces during thorough examinations and service visits.

Closing force limits are a final measure of safety to reduce the risks of entrapment injuries and lifts are fitted with safety devices to reverse door closing even before a door contacts the obstruction. Yet, for modern lifts designed to EN 81-20, entrapments can still occur. Improvements can be made to increase passenger safety and further reduce the entrapment hazard. Use of readily available technology and proven safety systems employed with other powered doors can be adapted for lift use to achieve this.

Lift owners and duty holders can take simple steps to reduce the risk of door crushing injuries to passengers. Application of simple warning signs to lifts may deter passengers from using their hands or arms to stall a closing lift door and would be a cost-effective improvement. Additionally, implementing extra checks to the routine testing of lift car alarms such as a functional test of the non-contact safety device and a physical check of the lift doors should also be considered. These measures will reduce the risk of injury to lift passengers and demonstrate a proactive approach to fulfil their obligations to protect the public and workers.

REFERENCES

[1] Elevators Ltd, *How Common Are Lift Accidents?* (2017)

[2] BSI, *EN 81-20:2020, Safety rules for the construction and installation of lifts. Lifts for the transport of persons and goods. Passenger and goods passenger lifts.*

[3] BSI, EN 14752:2019, *Railway applications. Bodyside entrance systems for rolling stock.*

[4] BSI, BS 7036-1:1996, *Code of practice for safety at powered doors for pedestrian use. General*.

[5] BSI, BS 7036-2:1996, *Code of practice for safety at powered doors for pedestrian use. Straight and curved sliding doors and prismatic and folding doors.*

[6] BSI, BS EN 16005:2012, *Power operated pedestrian doorsets - Safety in use - Requirements and test methods.*

[7] Mauser, F. and Mewes, D. *International Journal of Occupational Safety and Ergonomics Safeguarding Crushing Points by Limitation of Forces.* (2015)

[8] Maximum Security, *Curtain, waterproof outdoor/indoor intrusion detector with curtain field-of-view.*

BIOGRAPHICAL DETAILS

Daniel Meekin is a Senior Engineer for Zurich Engineering UK within their Technical Standards department. This extended abstract is summarized from a dissertation for his Bachelor of Engineering First Class with Honours in Mechanical Systems Engineering completed late 2021.

Challenges to Drafting a Standard for the Evacuation of Disabled People Using Lifts

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Keywords: Lifts, elevators, evacuation, codes, standards, capacity assessment, minimum lift car dimension.

Abstract. A standard for the design of a lift to be used for the evacuation of those who cannot easily use the stairs (an evacuation lift) ideally needs to respect different strategies for the evacuation of a building. In the case of evacuation due to fire the building design needs to protect the evacuation lift for at least the duration of the evacuation. Building design and management aspects vary according to the type of building and are subject to national building regulations which vary across different territories (they are not harmonized at a European level). This might partly explain a lack of convergence of evacuation lift solutions during a period where the use of lifts for evacuation has been widely discussed. In looking at evacuation lift provision and capacity, key considerations are: how many people might need or wish to use lifts for evacuation; and how can those most at need be prioritised? These challenges are discussed with reference to the development of a draft European Norm prEN 81-76 for evacuation lifts and in the context of undertaking a capacity assessment for the number of evacuation lifts which might be needed. This paper is written from a UK context.

1 INTRODUCTION

Building Regulations in many territories including the UK have set requirements for accessibility for all including disabled people. While setting the general requirements to consider the means of escape in case of fire, many have lagged in setting such clear requirements for the evacuation of disabled people. Especially in residential buildings, building design is often on the basis that occupants will "*stay put*" in the event of fire, based on effective compartmentation. There is considerable debate in the UK about the provision of means of escape for disabled people, for example, if compartmentation fails. Any changes in regulations or guidance in this area pose considerable challenges, especially for existing buildings.

Building regulation guidance and British Standards have for many years recognized the possibility of using lifts for the evacuation of disabled people [1, 2]. The evacuation lift described in these standards has been based on an evacuation assistant taking control of the lift car by operating an evacuation lift switch and then using the car controls to drive to floors where people await evacuation. This use of an evacuation lift, as part of a managed evacuation, presents challenges when applied to buildings such as residential buildings and (small) multi-tenant buildings where there would not usually be a team which could quickly mobilize and who could take charge of an evacuation.

A number of authors have recognized the potential benefits of using lifts for the evacuation of disabled people. Hewitt [3] reviewed the need for carry-down procedures to evacuate people not able to use stairs unaided and concluded that such procedures presented building management with very significant problems and presented evidence of the cost-effectiveness of using evacuation lifts. O'Loughlin, Wiles and Ryan [4] have advanced alternative concepts for evacuation lifts.

Work has been underway at CEN, the European standardisation body, on the development of a standard describing new lifts used for the evacuation of disabled people and a draft for public comment was recently published [5].

A standard for the design of a lift to be used for the evacuation of disabled people and those with difficulty in using stairs needs to respect different strategies for the management of evacuation of a building. In the case of evacuation due to fire, the building design needs to protect the evacuation lift for at least the duration of the evacuation. Since both the *management* of the lift during an evacuation and the *design of the building* are developed between a number of different specialisms and experts, it is clear that this is a multi-disciplinary and potentially complex task. In Europe, although lift requirements are usually harmonized across CEN countries, building design requirements are determined by national building regulations.

It should be noted that CEN lift standards are limited in the guidance they can provide for aspects beyond the lift specification such as the building design elements necessary for protecting an evacuation lift and interfacing it with the building systems.

In a UK context, the building design elements should follow guidance to the Building Regulations and either follow standards for the fire safety of buildings such as BS 9991 or BS 9999, or take an alternative fire engineered route.

Having identified the importance of the building's evacuation strategy for the operation of evacuation lifts, how might a lift operate in response to commands from the building management system (BMS)? The options include the following.

- **Remove the lift from service**. Lifts not intended to be used in the event of fire, for the use of firefighters or evacuation lifts, could be removed from service e.g. using the methodology of EN 81-73 [6]. The lift car would be recalled to the exit floor, allowing passengers to exit the lift car, and then be removed from service. Since the scope of EN 81-73 specifically excludes lifts that remain in use in the event of fire (lifts for the use of firefighters and evacuation lifts), it is not applicable to these types of lifts. However, a similar methodology to EN 81-73 could be used to remove an evacuation lift from service if it could be unsafe to use e.g. fire detected in the lift spaces by a suitable fire detection and alarm system.

- **Recall to exit floor to await evacuation assistant to take control of the lift**. The evacuation operation described in BS 9999:2017, Annex G [2] is based on an evacuation assistant taking control of the lift. At the time of writing, this is the only evacuation lift operation described in British Standards and has remained relatively unchanged since first included in British Standards in 1988 [1]. After recall to the exit floor, an evacuation assistant/ driver can use the evacuation lift to drive to the floors where there are people needing the lift for evacuation i.e. who cannot readily use the stairs. This has advantages of simplicity.

- **Automatic (self-evacuation operation)**. This was suggested by O'Loughlin, Wiles and Ryan [4] who noted that "*challenges that would need to be addressed include the applicable control logic, prioritisation of the lift response depending upon the fire scenario, the level of information provided to the user(s), and overcoming the traditional instruction of 'do not use the lifts in the event of fire*'". Such an operation would need the BMS to determine whether it would be sufficiently safe, raising questions about its decision making and security. Other questions revolve around ensuring that lifts in an automatic operation are effectively prioritised for the evacuation of those depending on lifts.

How the lift might behave under automatic evacuation operation is further considered below.

Note: Control of an evacuation lift described in BS 9999 by an evacuation assistant has superficial similarities to the control of a firefighters lift described in EN 81-72. Although it might be technically feasible to apply evacuation lift requirements in addition to the requirements of EN 81-72, use of the lift for evacuation should cease when the lift is recalled from the firefighters lift switch.

2 EVACUATION LIFT WITH AUTOMATIC EVACUATION OPERATION

A CEN standard is limited in the guidance it can provide for aspects beyond the lift specification. In the case of a driver assisted evacuation described above, the basic specification is mature and well understood [8]. However, in the case of a novel solution such as a lift for self-evacuation, the lack of additional guidance in a CEN standard for interface issues might make the introduction and application of the standard more difficult. There is therefore scope for national standards and guidance to address this gap to help with the safe application of a CEN standard.

The draft BS 9991 [7] recognises that automatic evacuation operation should not be used unless there is a building management system (BMS) in place to:

a) recall the lift;

b) provide the automatic evacuation signal; and

c) where landing calls are to be accepted only from priority floor(s), signal the priority floor(s) to the lift controller.

The safety of the lift also depends on there being a fire alarm and detection system covering the lift spaces and lift lobbies to suspend evacuation service (similar to the operation in EN 81-73).

Clearly, resilience and decision making are essential elements of the BMS.

A crucial consideration for the building design is how long the evacuation lift should be available to operate to evacuate people who would have difficulty using the stairs, and hence the minimum period for which it needs to be protected from fire, minimum autonomy time of a secondary power supply etc. It is assumed to be two hours for a firefighters lift, which is professionally supervised. This is where a consideration of the traffic flow is required using well-established methods based on an estimation of the number of people needing to be evacuated by lift, and the intended use/operation of the lifts.

The proportion of people on a given floor of a building who might need the use of lifts for evacuation can be categorized as:

1. Those unable to use the stairs – even for a single floor.

2. Those who would have difficulty using the stairs to evacuate from their floor of the building. This proportion would increase with floor height to take account of their impairments and factors such as fatigue. For simplicity, this proportion includes those who start to evacuate by stairs but due to fatigue or injury need evacuation lift service from a lower level.

3. There is a further proportion who, although the lift would be designated for those with difficulty using the stairs, would opt to use a lift that is available even though they could use the stairs.

Clearly, in considering the specification of evacuation lifts, it is important to estimate the demand for them, how to prioritise their availability for intended users (items 1 and 2), and how to control or mitigate use by others which might have an undesirable impact on their availability (item 3). This paper reviews a number of sources which have tried to assess the proportions of building population which might use evacuation lifts. It is noted that in these sources, building users were surveyed for their intentions based on the lifts being fully available to all.

There is an underlying concern that specification of the number of evacuation lifts based on estimates of the users in categories 1 and 2 might result in the under-provisioning of evacuation lifts, if used by a significant number of users in category 3.

The strategies available to address demand from the third group above are:

- Evacuation lift controls are for use by evacuation assistants who take control of the lift during an evacuation. This is the approach taken in the UK with the first publication in 1988 of BS 5588-8 [1] through to more recently BS 9999 [2]. This strategy is applicable where suitably trained assistants are available e.g. managed buildings.

- Where lifts are to operate automatically without trained assistants, then their application could be restricted to buildings of up to a maximum height/ number of floors. At such a height, most users would be assumed to opt to evacuate by stairs.

- Where lifts are to remain in operation without trained assistants and the building height is not restricted then all the lifts used for regular access could be specified as evacuation lifts to ensure adequate provision or the number of lifts should be selected according to a more detailed process. This is the basis of ISO/TS 18870 [9] which provides more guidance in this more complex scenario.

3 DEMAND FOR EVACUATION BY LIFT

The implications for the specification and number of evacuation lifts were briefly discussed in section 2. This recognized that demand for use of lifts for evacuation relative to floor height consisted of a fixed demand (item 1) and demand which would vary according to floor height (items 2 and 3).

3.1 Estimate of numbers of population requiring a lift to evacuate

The UK Government [10] estimates that 15% to 22% of people have a disability and that of all disabled people, 46% to 63% are estimated to have a mobility impairment. Multiplying the low and high values gives a range of 6.9% in the low scenario, 13.9% in the high scenario, and a central estimate of 10.1%. Although noting that this assumption is uncertain, and might be an under-estimate if significant numbers had not self-identified. A figure of 10% has been used elsewhere such as DD CEN/TS 81-76 [8].

The UK Government data referenced above estimating that 22% of the population have a disability, also provides details on impairment type with 46% of all disabled people reporting mobility problems and 33% reporting stamina/breathing/fatigue problems. Other categories with temporary impairments should also be considered such as people with injuries, pregnant women and companions/partners of the mobility impaired person. Taken together, these might indicate greater numbers of the population needing to use a lift for evacuation.

While such broad estimates might provide baseline assumptions where no better information is available, figures relating to the type of building and its intended use might be used when available. It is prudent also, in providing fixed assets and building space, to consider how changes over the life of the building could impact the figures used in design. Trends in the general population to longer life expectancy and co-morbidities including obesity would argue for a conservative (higher) figure to be used, noting that in social housing, 40% of occupants might have mobility issues and 40% might have stamina problems.

It is difficult to find accurate data on the numbers of wheelchair users as Hewitt [3] observed but estimated 1.5%. Users of wheelchairs and mobility scooters would need attention not only to ensure a suitable minimum size of evacuation lift car, but also because a wheelchair user would occupy the space of several ambulant disabled passengers.

3.2 Research into assessing the potential demand for evacuation lifts

While some broad conclusions can be drawn from evacuations due to real emergencies, the data available from post evacuation surveys is often not sufficiently detailed so other sources, typically surveys, are useful.

Owing to the lack of use of lifts for evacuation, these studies have been undertaken where the general expectation is not to use lifts. Unless noted otherwise, the surveys were conducted on groups who have not been trained to use lifts as part of an evacuation.

Heyes and Spearpoint [11] reported on post-evacuation drill surveys of students and staff of the University of Canterbury, New Zealand, and online surveys completed by workers (the majority were engineers) from Arup from locations in Perth, San Francisco and Singapore. The post-evacuation drill survey was given to students and staff after evacuating two buildings on campus as part of a drill. 91 people completed surveys about their evacuation experience and were asked if they would consider using lifts if it were acceptable to do so. Participants were divided into two groups; "*educated*" who had been taught that lifts could be used as part of evacuation and "*uneducated*" who were not. In the online survey, 138 participants were asked to judge how imaginary characters would behave within a hypothetical evacuation, their understanding of evacuation procedures in their building, the number of stairs that they would be capable of evacuating down and what concern they would have for using lifts/stairs during an evacuation.

The data, from 5 to 60 floors was presented in a graph to which a linear regression line was fitted to predict the proportion of lift users given the floor level:

$$p = 1.14f + 5.3 \qquad 5 \leq f \leq 60 \text{ floors} \tag{1}$$

where:

p is the percentage of occupants to use the lift (%)

f is the floor level of the building

A goodness of fit value (R^2) of 0.877 was achieved.

Heyes and Spearpoint [11] reported a negative correlation between willingness to use lifts and the waiting time to evacuate. The proportion of occupants willing to use the lift was seen to reduce as waiting time increased and a further linear regression was used to describe the dependence of the proportion on waiting time.

Kinsey 2011 [12] and Kinsey et al 2012 [13] presented data drawn from online surveys on the overall proportion of participants that would consider using a lift/stair for a number of floor ranges. This showed increasing proportions of participants that would consider using the lift increasing as the floor number/height increased. They noted that approximately 10% of the population would use a lift even if located on the lowest floors i.e. 2-10. The proportion of the population that would use the lift increased to approximately 80% at floor range 31-40 and remained at this level for the higher floor ranges. In addition, the results suggested that when located on or above floors 21-30, the majority of people on each floor would elect to use the lift compared to the stairs. Above floor 30, approximately 20% of the population were not prepared to use the lifts to evacuate irrespective of floor number/height.

The relationship between proportion of floor population who would use the lift to evacuate and the floor number presented by Kinsey et al [13] figure 5 is reproduced in Figure 1.

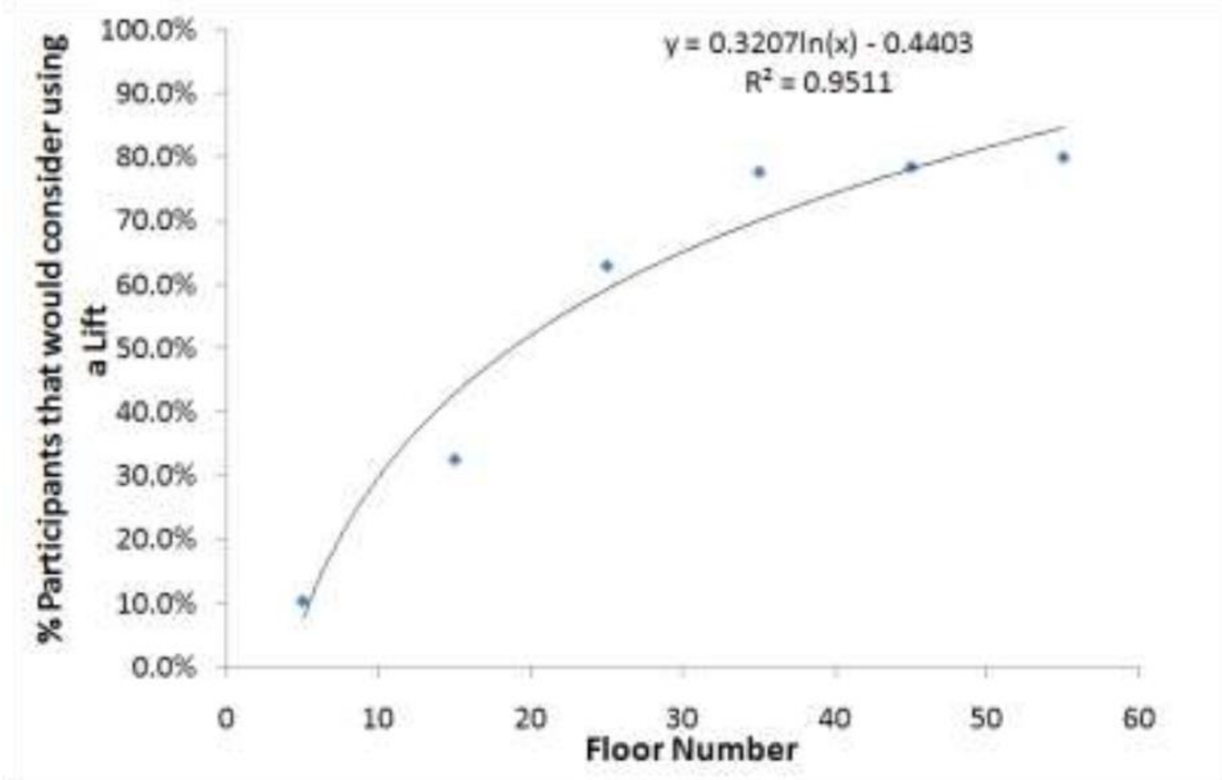

Fig 1: Proportion of participants that would consider using a lift according to floor number
(Figure 5 from Kinsey et al [13])

The data presented in Figure 1, the mid-points of each floor range (e.g. 5, 15, 25 etc) with the respective proportion of participants that would consider using lifts during the evacuation has been plotted. Using regression analysis, the relationship between the floor number and percentage of participants shows the following formula to approximate the data:

$$p = 0.3207 \ln(f) - 0.4403 \text{ for } 5 \leq f \leq 55 \quad (2)$$

Where 'p' equals the proportion of people that would consider using a lift and 'f' represents the floor number that the people are initially located on above ground level. An R^2 goodness of fit value of 0.95 was obtained from this formula which suggests it to be a good predictor according to the data collected. It should be highlighted that this formula is only applicable between floor ranges 5-55 (the lower and upper mid points of the floor ranges).

Jönsson and Andersson [14] in a survey of 10 of Sweden's tallest buildings found that the floor a respondent was on was a clear factor in their perception of risk and whether they said that they would use a lift to escape. They found that the relationship was linear (2% at 2 floors up to 21% at 24 floors).

Ding et al. [15] reported on experiments in a 10 floor building in Beijing using 45 students; 27% were prepared to use lifts before education and 40% after briefing. They were asked to complete questionnaires which showed the proportion willing to use lifts up to 75% at 20 floor and 100% for 50 floors. Figure 2 reports the results from Ding et al. Although it can be noted that the general form of the results is similar to Kinsey et al., the proportions willing to use lifts are generally 20% or more greater than the equivalent figures reported by Kinsey et al. for the proportions that would consider using the lift. It might be observed that even at large numbers of floors, some residual proportion would be expected to use stairs.

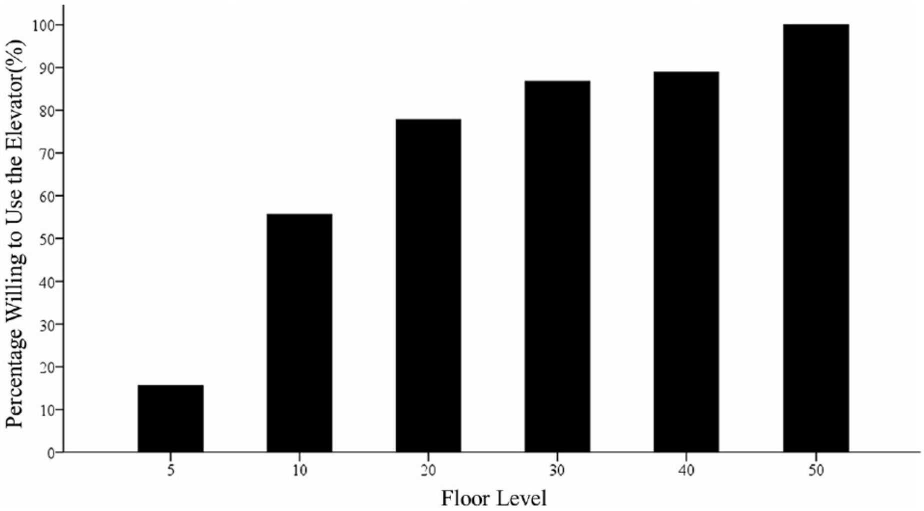

Figure 2: Cumulative percentages of participants who want to use elevators (Figure 3 from Ding et al)

3.3 Demand for lifts for evacuation – conclusion

Except for very low building heights/ lift travel distances, any baseline estimate of numbers of people needing to use lifts for evacuation either owing to not being able to use the stairs or because of stamina/breathing/fatigue issues is likely to be significantly increased by those seeking to use lifts to evacuate – either because of stamina/breathing/fatigue issues or because they have otherwise opted to use lifts.

The implications for specification of evacuation lifts specifically allocated for the use of those needing lifts for evacuation are clear:

- Except at very low floor heights, the estimate of floor population needing to use a lift for evacuation should take account of this additional demand if the needs of those relying on lifts are not to be compromised.
- Except in low rise buildings, if there is a simultaneous evacuation strategy, all passenger lifts should be specified to be used for evacuation. This takes the specification of evacuation lifts away from the scope of prEN 81-76 (evacuation of disabled people) [5] and to the scope of ISO/TS 18870 (evacuation of the general building population) [9].
- For modelling purposes, the figures from Kinsey et al. would be a good basis, adjusted to include a minimum demand even for low rise lifts.

4 INFLUENCE OF EVACUATION AND MANAGEMENT STRATEGY

As discussed earlier, evacuation lifts might be specified with at least two generic ways of working:

1. **Driver assisted evacuation lift** An evacuation lift switch is provided which allows a trained evacuation assistant to control the lift. This is not further discussed in this section because the evacuation team should be able to direct the lift to the floors where evacuation is needed.
2. **Automatic evacuation operation** Signals from a Building Management System (BMS) switch the lift into an evacuation operation which shuttles between the exit floor and the priority floor to be evacuated. Key issues are the BMS determining that the environment allows the evacuation lift to operate and how the landing calls are prioritised.

Taking the “automatic evacuation operation” and looking at the way landing calls might be prioritised, prEN 81-76 [5] proposes that the priority of the landing calls would be based on distance from the exit floor with the furthest landing call getting highest priority, if not otherwise specified by the evacuation strategy.

The landing calls would usually be connected directly to the lift control system and so the lift control system could readily prioritise landing calls based on their distance from the exit floor and would need only a simple interface with the BMS to achieve this. Such a landing call prioritisation might be appropriate for very simple low rise buildings but suffers from not being able to prioritise calls from floor(s) where fire is detected and the immediately adjacent floors.

Where a phased evacuation is needed e.g. fire floor and floors immediately adjacent are prioritised for evacuation over those more distant from the fire floor, this would need to be specified as part of the definition of the evacuation lift. The interface between BMS and lift controls in this case would need to be more sophisticated to communicate the prioritisation to the lift controller to allow the lift control system to prioritise the landing calls presented to it.

It is suggested that in many buildings there would be a need to specify the evacuation strategy, the prioritisation for landing calls, and the interface between the BMS and lift control system to accomplish this. Where the prioritisation of landing calls based on their distance from the exit floor is a default, it would be important that these are specified as part of the negotiation of the evacuation lift.

5 PLANNED EVACUATION TIME

Any capacity assessment would be based on an estimated number of people to be evacuated in a given time; the number of lifts required being strongly related to this time. A figure for maximum planned evacuation time is therefore essential for undertaking a capacity assessment.

In the case of evacuation due to fire, a distinction can be made based on the relationship between the maximum planned evacuation time and the expected time for attendance by the fire and rescue services and commencement of firefighting operations.

In the case of simpler buildings and where relatively small numbers need to be evacuated using a lift, it might be feasible to complete the evacuation before commencement of firefighting operations. This would be required for an evacuation lift which is also specified to be firefighters lift so that it is available for use by firefighters, unless other dedicated evacuation lift(s) are provided.

The maximum planned evacuation time would have implications for the evacuation management strategy as well as for building design (beyond the immediate specification of an evacuation lift) to ensure adequate protection and resilience including:

- the level of fire protection to the evacuation lift lobbies, well and machinery spaces;
- the endurance/autonomy time and capacity of secondary power supplies to cope with the planned demand from evacuation lifts and also lifts for firefighters use;
- water management to prevent water from entering the lift well;
- how evacuation would be carried out during firefighting operations.

6 CAPACITY ASSESSMENT

6.1 The need for capacity assessment for evacuation lifts

The new London Plan came into force in March 2021 and set out a framework for how London should develop over the next years. In the new London Plan, policy D5(B5) on inclusive design includes a minimum of one evacuation lift per core (or more subject to capacity assessments) to be provided for the safe and dignified emergency evacuation of people who require level access from the building.

The Greater London Authority published draft Fire Safety London Plan Guidance (LPG) in February 2022 with guidance to support policy D5(B5) [16]. This included the following on capacity assessment.

> *"**i) Capacity assessment***
>
> *6.3.3 A capacity assessment should be carried out to establish the number and size of evacuation lifts that the development will need to provide. This assessment should set out:*
>
> - *the likely number of occupants and visitors*
> - *the nature of the occupants (for example the likelihood that occupants may require evacuation in a wheelchair or bed) and any other assumptions the capacity is based on*
> - *the calculation of the evacuation lift capacity required*
> - *the evacuation lift capacity that would be provided*
> - *any potential risks during evacuation due to the anticipated capacity".*

In addition to these items, a number of other important determinants should be considered which were discussed above:

- The evacuation strategy which will determine the type of evacuation and how the evacuation lift is used e.g. if driver assisted, the presence of the driver needs to be considered;
- A planned evacuation time is an essential requirement for any capacity assessment seeking to establish the number and size of evacuation lifts to evacuate a given number of people in the planned evacuation time.

The draft LPG does not seek to provide guidance on how such a capacity assessment should be undertaken. It can be observed that specialist guidance on evacuation lift capacity assessment would not be appropriate to sit in the LPG or standards such as BS 9999 [2] or draft standards such as the revision of BS 9991 [7] or prEN 81-76 [5]. Hence other guidance is needed.

The draft LPG in relation to evacuation lift car size includes: "No specified lift size, but likely to be larger to accommodate beds or stretchers". BS 9999:2017 and prEN 81-76 refer to BS EN 81-70 [18] for lift car sizes. It can be noted that car sizes 1 and 2 in BS EN 81-70 could not accommodate a stretcher or bed. This suggests that the smallest size of evacuation lift which should be considered is type 3 in BS EN 81-70:2021. See also Appendix 1 "Consideration of minimum evacuation lift car sizes – UK context".

Unpublished data from a BRE study has been used to estimate the likely space used by a range of users with different disability types based on published UK data such as in reference [10]. Based on these, an average area for each disabled user of 0.42 m^2 is suggested. This represents a packing factor of two compared with the average space occupied by an adult for lift traffic considerations of 0.21m^2 from Barney [17]. A packing factor of two has been assumed to account for factors which might increase the space needed by people being evacuated e.g. to access and hold a handrail, account for any walking aids, to account for additional area taken by people with higher body mass index, space taken by those with helpers, those using wheelchairs etc.

Table 1 lists the car sizes listed in BS EN 81-70 [18] and uses the average area per user of 0.42 m^2 to arrive at maximum average passenger occupancy for each car size. In the case of the driver assisted car, the driver has been assumed to require 0.21 m^2. The resulting number of people has been rounded down to the next lowest integer.

TABLE 1: Disabled persons occupancy during emergency operation

Rated load, *Q* (kg)	**Car type from BS EN 81-70:2021**	**Car dimensions width (m) x depth (m)**	**Nominal available car area, A_c (m^2)**	**Driver assisted car capacity, P_{de}**	**Automatic evacuation car capacity, P_{ae}**
630	2	1.1 x 1.4	1.54	3	3
1000	3	1.1 x 2.1	2.30	5	5
1000	4	1.4 x 1.6 1.6 x 1.4	2.24	5	5
1275	5	1.4 x 2.0 2.0 x 1.4	2.80	6	6

Notes:
P_{de} and P_{ae} are the integer values of A_c/0.42 taking account of a small area in the car entrances.

The resulting car capacity is a key determinant of the capacity assessment for evacuation of disabled people. As was discussed in section 3, even from moderately low floor heights, this demand for evacuation lifts is likely to be supplemented by those opting to use lifts. The capacity assessment would need to take account of this demand and its increasing proportions of floor populations as floor height increases. When estimating their space taken, it would be reasonable to assume a packing factor of one, i.e. the cars would accommodate approximately twice the automatic evacuation car capacity.

The following material in this section is adapted from material from Dr Gina Barney, who is acknowledged with thanks. The following proposes two methods of capacity assessment:

1. A simple calculation suitable for non-lift specialists e.g. architects, fire consultants and fire engineers giving a “ball park” view;

2. a more advanced method for competent lift traffic designers to use and where the results of the simple method need to be elaborated such as for a more complex building design. For example to fit the “jigsaw” of irregular spaces into a rectangular car.

The calculation method below is based on established measures to assess the round trip time and handling capacity of lifts adapted for use in the evacuation situation.

Assumptions made to provide the simple calculation method are:

- The automatic evacuation lift shuttles between the exit floor and the floor for evacuation where the middle floor evacuated is a distance d_m from the exit floor;

- Rated speed (v) is 1.0 m/s (increasing rated speed has only a small benefit);

- Round Trip time (RTT) consists of:

Time to travel between exit floor and evacuation floor and back	$2*d_m/v$
Time to open and close doors (t_d = 6 seconds) at the two stops	$+ 2*t_d$
Time for passengers to board and exit (t_l = 5 seconds per passenger)	$+ 2*P_{ae}*t_l$

Round Trip time (RTT) = $2*d_m + 2*6 + 2*P_{ae}*5 = 2d_m + 12 + 10*P_{ae}$

- Round trips per 5 minutes = $300/RTT$
- Persons evacuated per 5 minutes = $(P_{ae}*300)/(2*d_m+12+10P_{ae})$ (1)

6.2 Simple calculation method for buildings with highest floor not greater than 18 m

$$\text{Number of persons evacuated in 5 minutes per evacuation lift} = \frac{300\times P_{ae}}{2\times d_m+12+10P_{ae}} \tag{2}$$

P_{ae} is the possible occupancy of the lift car taken from Table 1. For a driver assisted operation, P_{de} can be used.

6.3 Advanced calculation

A more complex calculation or simulation is needed where automatic evacuation operation is used and where the floor heights are such that part of the building population is likely to use the lifts. There are well established principles on which advanced calculation or simulation would be based [19]. No doubt the introduction of a standard for automatic evacuation lifts would be a catalyst for more work in this area and further guidance.

7 CONCLUSIONS AND FURTHER WORK

In a UK context, documents such as the London Plan are likely to lead to a larger proportion of passenger lifts in new buildings being specified for disabled people to evacuate. A new European Norm (EN) is expected which will provide a much enhanced specification for driver assisted evacuation (compared with legacy evacuation lifts described in British Standards) and an entirely new (in standards) specification for an automatic evacuation operation.

A number of issues linked to the specification and planning of evacuation lifts have been discussed. It is suggested that guidance on these and other issues should be developed to support the implementation of a European Norm for evacuation lifts. A European Norm for lifts would set normative requirements for an evacuation lift and would be constrained in the guidance it could give for building design aspects. However, much of this guidance would be more appropriately implemented at national level.

The following areas are highlighted for further guidance to be developed especially to support the introduction of a new evacuation lift standard.

1. Guidance on capacity assessment to estimate the likely number of evacuation lifts based on a number of factors considered in this paper. This could include simple tools for low-rise buildings and more sophisticated methods for taller and more complex buildings.

2. Guidance on estimating the proportion of floor populations who could be expected to use lifts for evacuation in addition to disabled people depending on the lifts for evacuation with default figures to be used where more specific and detailed studies are available.

3. Consideration of the maximum planned evacuation time as a key determinant of the number of evacuation lifts needed with guidance on the implications for protection to be specified for evacuation lifts to achieve the required level of resilience.

4. Recommendation that evacuation lifts have minimum lift car dimensions as BS EN 81-70:2021, type 3 (1100 mm x 2100 mm).

5. The introduction of automatic evacuation operation would be a significant change which should be supported by further guidance. Landing call prioritisation must be specified based on the evacuation strategy and suitable interfaces between the building management system and lift controls specified accordingly.

These are all in the context of developing standards and guidance for new evacuation lifts in new buildings. It might be anticipated that there could be a call for guidance for how existing passenger lifts could be improved to provide for the evacuation of disabled people from existing buildings. In a UK context, this would need to consider not only the improvement of existing evacuation lifts (installed since 1988) but also the improvement of existing passenger lifts to provide for the evacuation of disabled people. Framing useful guidance in this area will be a challenge.

8 REFERENCES

[1] British Standards Institution (1988) BS 5588-8:1988; *Fire precautions in the design and construction of buildings —Part 8: Code of practice for means of escape for disabled people*. London: BSI.

[2] British Standards Institution (2017) BS 9999:2017; *Fire safety in the design, management and use of buildings - Code of practice.* London, BSI.

[3] Hewitt, J *Accessibility for everyone – evacuation for only some?* MSc Dissertation – the University of Reading (2009)

[4] O'Loughlin, E, Wiles, H and Ryan, M *Alternative Escape Route* In; CIBSE Journal July 2021 pp40-42 accessed 08.05.2022: http://portfolio.cpl.co.uk/CIBSE/202107/40/

[5] British Standards Institution (2022) Draft for public comment: prEN 81-76: *Evacuation of persons with disabilities using lifts.* London, BSI.

[6] British Standards Institution (2020) BS EN 81-73:2020; *Safety rules for the construction and installation of lifts — Particular applications for passenger and goods passenger lifts — Part 73: Behaviour of lifts in the event of fire*. London, BSI.

[7] British Standards Institution (2021) Draft for public comment: *Draft BS 9991 Fire safety in the design, management and use of residential buildings – Code of Practice*. London, BSI.

[8] British Standards Institution (2011) DD CEN/TS 81-76:2011; *Safety rules for the construction and installation of lifts — Particular applications for passengers and goods passenger lifts — Part 76: Evacuation of disabled persons using lifts*. London, BSI.

[9] British Standards Institution (2014) PD ISO/TS 18870:2014. *Lifts (elevators) — Requirements for lifts used to assist in building evacuation*. London, BSI.

[10] HM Government (2022) Family Resources Survey: financial year 2020 to 2021, 31 March 2022. Accessed 2 June 2022: https://www.gov.uk/government/statistics/family-resources-survey-financial-year-2020-to-2021/family-resources-survey-financial-year-2020-to-2021

[11] Heyes, E and Spearpoint, M, *Human behaviour considerations in the use of lifts for evacuation from high rise commercial buildings*, 2009: Department of Civil Engineering, University of Canterbury

[12] Kinsey, M J *Vertical transport evacuation modelling* PhD Thesis, University of Greenwich 2011

[13] Kinsey, M J, Galea, E R and Lawrence, P J *Human Factors Associated with the Selection of* 1*Lifts/Elevators or Stairs in Emergency and Normal Usage Conditions* In: Fire Technology, August 2012.

[14] Jönsson, A, Andersson, J and Nilsson, D *A Risk Perception Analysis Of Elevator Evacuation* In High-Rise Buildings in Fifth International Symposium on Human Behaviour in Fire. 2012. Cambridge, UK: Interscience Communications.

[15] Ding, N., Zhang, H. & Chen, T. *Experimental study of egress selection behavior between stairs and elevators during high-rise building evacuation*. In: Fire Technology 55, 2019.

[16] Fire Safety London Plan Guidance (LPG), https://www.london.gov.uk/sites/default/files/fire_safety_lpg_consultation_version_-_planning_11_feb_22.pdf Greater London Authority, February 2022

[17] Barney, G *Rated Load and Maximum Available Car Area* In: Elevator World UK, 2022/02, Issue 111 pp60-62, 64.

[18] British Standards Institution (2021) BS EN 81-70:2021: *Safety rules for the construction and installation of lifts — Particular applications for passenger and goods passenger lift Part 70: Accessibility to lifts for persons including persons with disability*. London, BSI.

[19] CIBSE Guide D:2020, *Transportation systems in buildings*. London: CIBSE

BIOGRAPHICAL DETAILS

Nick Mellor is the Managing Director of the Lift and Escalator Industry Association (LEIA) where he has worked since 2012 and has been in the lift industry since 1992. LEIA is the trade association in the UK for the lift and escalator sector which, along with the University of Northampton and the CIBSE Lifts Group, co-organise the Lift & Escalator Symposium. Nick was in the inaugural cohort on the MSc in Lift Engineering from the (now) University of Northampton from which he graduated in 2002. He is an Associate Lecturer and visiting fellow at the University of Northampton. Nick chairs the BSI's MHE/4 lift and escalator committee where he has been involved in the development of various British Standards. He is a BSI delegate to various European (CEN) and International (ISO) working groups including those considering firefighters lifts and lifts for evacuation. Nick is the principal author of two chapters of CIBSE Guide D:2020 and has published a number of papers.

APPENDIX 1: Consideration of minimum evacuation lift car sizes – UK context

This appendix considers the current standards in a UK context and whether the minimum lift car dimensions currently specified are sufficient for moving a person on stretcher.

It is understood that many UK ambulance trusts use stretchers which have lengths between 1450 mm and 1680 mm when "fully shortened" with total lengths when fully extended of between 1930 mm and 2045 mm (depending on make and type). A car depth of 2100 mm would therefore be sufficient to accommodate these.

Minimum lift car sizes for accessibility to buildings are listed with their accessibility levels in BS EN 81-70:2021; *Accessibility to buildings Accessibility to lifts for persons including persons with disability*. Car type 3 (1100 mm x 2100 mm) is listed as allowing transport of stretchers. However, the standard does not specify minimum lift car dimensions for access to and use of buildings; this is left to Building Regulations guidance such as, in England, Approved Document M; *Access to and use of buildings*. The minimum car sizes (such as 1100 mm x 1400 mm) in Approved Document M do not allow for a person being moved on a stretcher.

Minimum lift car dimensions to allow for people on stretchers to be extracted from a building is related to the use of lifts for evacuation. BS 9991:2015; *Fire safety in the design, management and use of residential buildings – Code of practice* points to the recommendations in BS 9999:2017; *Fire safety in the design, management and use of buildings – Code of practice* which recommends that evacuation lifts are in accordance with the relevant provisions in BS EN 81-20 and BS EN 81-70. Building Regulations guidance, such as Approved Document B; *Fire safety* does not specify a minimum evacuation lift car size and references BS 9999. The conclusion is that these fire safety documents reference to BS EN 81-70 but do not specify which car type in that standard should be selected.

BS EN 81-72:2020; *Firefighters lifts* details a minimum car dimensions for firefighters lifts and has the following: *Where the intended use of the firefighters lift is to include evacuation, to accommodate such items as a stretcher or bed, then the minimum rated load shall be 1 000 kg and the minimum dimensions of the car 1 100 mm wide by 2 100 mm deep*.

At the time of writing a draft European standard, prEN 81-76; *Evacuation of persons with disabilities using lifts* is out for public comment. This document includes a minimum evacuation lift car size of type 2 according to EN 81-70:2003, Table 3 (car dimensions of 1100 mm x 1400 mm). If published as a British Standard, a future BS EN 81-76 would be referenced by standards such as BS 9991 and BS 9999 and by Building Regulations guidance.

If new lifts need to be specified to have minimum car dimensions to accommodate a person on a stretcher, at least car type 3 from BS EN 81-70:2021 will need to be referenced from Building Regulation guidance for fire safety and accessibility, and British Standards such as BS 9991 and BS 9999.

Setting Standards on Remote Monitoring & Diagnostic for lifts – A Singapore Context

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Keywords: Remote Monitoring and Diagnostics, Lift, Code of Practice

Abstract. The use of Internet of Things (IoT) with remote monitoring capability or Remote Monitoring & Diagnostics (RM&D) to carry out maintenance of lifts has been gathering momentum in recent years. The advantage of this over the traditional time-based maintenance is that it allows continuous tracking of lifts' operating condition for diagnosis of early fault detection, thus preventing unnecessary breakdowns and raising safety, reliability, and productivity levels. Recognising the importance of these benefits, the Building and Construction Authority of Singapore (BCA) had formulated the "Code of Practice for the Design and Performance of Remote Monitoring & Diagnostics Solution for Lifts" which aims to provide guidelines for RM&D solutions to be deployed in Singapore. This paper will first briefly discuss the structure of the code before moving to the 2 key areas of the code: "Monitoring Outcomes" and "Performance Indicators" which aim to provide a framework on the required monitoring areas and the evaluation of the effectiveness of the RM&D solutions respectively. Finally, there will be a brief discussion of the results of a local RM&D trial which was based on the code.

1 INTRODUCTION

In a densely built-up city State like Singapore, lifts are a vital mode of vertical transportation in buildings. Hence, proper and sufficient maintenance is essential to keep this equipment safe and reliable. Today, lifts in Singapore are required to be checked and serviced (where necessary) once every month, by skilled and trained technicians. For compliance, a properly maintained lift must meet the statutory requirements stipulated in the relevant legislation[1].

There are many different types of maintenance strategies used in the lift industry. Some common practices are as follows:

- Corrective maintenance. A category of maintenance carried out only when the lift experiences a breakdown.
- Preventive Maintenance. A maintenance method carried out at regular intervals to reduce the likelihood of premature asset failure. This includes TBM, CBM and PdM.
- Time Based Maintenance (TBM). Maintenance works are carried out at a planned interval. This may be based on manufacturer's recommendation or performed on a regular basis. In Singapore, monthly servicing is required by law.
- Condition Based Maintenance (CBM). This strategy requires condition monitoring and involves fixing the equipment before the conditions start to deteriorate beyond certain thresholds or boundaries.
- Predictive Maintenance (PdM). This maintenance method uses condition monitoring data and forecasts of failures using Artificial Intelligence techniques and repair or replacement will be carried out before the failure happens.

[1] Building Maintenance and Strata Management (Lift, Escalator and Building Maintenance) Regulations 2016

In recent years, Internet of Things (IoT) technology, which is basically the concept of connecting physical devices embedded with sensors, software and other technologies to the internet and having them to communicate and exchange data between themselves and with the cloud network (Oracle, 2022; Amazon Web Services, 2022), has advanced at a rapid pace. This helps to proliferate the use of CBM or PdM in many industries such as aviation, oil & gas, semi-conductor and sectors that involve the use of high capital cost equipment (Lai, et al., 2019). Such IoT enabled maintenance has the following advantages: (i) reduction in unnecessary maintenance leading to increased equipment availability, (ii) greater efficiency for maintenance personnel due to targeted maintenance, (iii) better planning for part replacement, (iv) lowering maintenance cost and (v) increased visibility of asset activities (Janelle, 2018; Lin, et al., 2002).

Given the above benefits, major lift companies such as Schindler, KONE, TK Elevator and Otis have started to roll out their IoT enabled CBM solutions in recent years (Schiller & Falge, 2018; Bourgeat, 2018; Beebe, 2016). At the same time, the Building and Construction Authority (BCA), a government agency in Singapore, is responsible for regulating the safety of lifts and escalators, has identified the use of IoT for lift maintenance as a long-term solution for manpower crunch issues and is encouraging companies to import this technology or develop them for use locally. For the purpose of this paper, we refer to IoT enabled CBM solution as Remote Monitoring & Diagnostics solution or RM&D solution in short.

In 2016, BCA convened the inaugural meeting of International Panel of Experts (IPE) on Lifts & Escalators to seek inputs on key issues relating to lifts and escalators. One of the topics covered was on Remote Monitoring & Diagnostics (RM&D). Following the IPE, BCA started to look in depth into the RM&D technology and how the lift industry could benefit from it. We also embarked on learning trips to countries where RM&D solutions had already been established. Through the process, we identified the lack of standards as one of the challenges in proliferation of RM&D technology. To address this, it is necessary and important for BCA and the local lift industry to set certain minimum requirements to level the playing field and ensure that it is effective. This then led to the publication of a code in August 2022 for the development and usage of RM&D solutions in Singapore's lift industry, which is the "Code of Practice for the Design and Performance of Remote Monitoring & Diagnostics Solution for Lifts"[2]. For this paper, we will first discuss the structure of the code before moving to describe the system architecture of an acceptable RM&D solutions. In this same section, we will also focus on 2 key areas of the code: "Monitoring Outcomes" and "Performance Indicators" which aim to provide a framework on the required monitoring areas and the evaluation of the effectiveness of the RM&D solutions respectively. Finally, there will be a brief discussion of the results of a local RM&D trial which was based on the code.

2 STRUCTURE OF THE CODE

The structure of the code is similar to lift related standards such as EN81-20/50 and Singapore standards SS 550. Like these standards, the code on use of RM&D solutions in lifts starts with the scope as well as key definitions that are extensively mentioned in the subsequent clauses. Following this, the code will then define the minimum requirements for lifts connected to RM&D solutions vis-à-vis the following sections: (i) System Architecture (ii) Data

[2] The code of practice can be downloaded from the URL: https://www1.bca.gov.sg/docs/default-source/docs-corp-regulatory/lifts-and-escalators-legislation/code-of-practice-for-design-and-performance-of-remote-monitoring-and-diagnostics-solution-for-lifts-(final).pdf?sfvrsn=cf5164cb_0

Visualisation (iii) Remote Testing, Intervention and Control and (iv) Cyber Security Requirements. At the end of the code, there are informative annexes on the Performance Indicators and Technical and Non-Technical Faults.

3 SYSTEM ARCHITECTURE

A review of available literature shows that there are no standards related to RM&D for lifts. However, there have been extensive research carried out on the theory, methodology and application of CBM. To define the system architecture, these were studied and references from available CBM standards such as ISO 17359, Condition monitoring and diagnostics of machines - General guidelines were used. ISO 17359 outlines the condition monitoring procedure for a general manufacturing process, factors influencing condition monitoring, a list of issues affecting equipment criticality (e.g., cost of machine down-time, replacement cost), and a table of condition monitoring parameters (such as temperature, pressure, and vibration) for various machine types. ISO 17359 also presents multiple examples of tables showing the correlation of possible faults (e.g., air inlet blockage, seal leakage, and unbalance) with symptoms or parameter changes. Furthermore, ISO 17359 shows an example of a typical form for recording monitoring information. The basis is that such system developed for CBM should be similar as after all, lifts are also electro-mechanical systems. The result is that we will require the system architecture to consist of the following combinations:

a) Data Acquisition
b) Data Pre-processing
c) Data Analytics

4 DATA ACQUISITION

Just like any other CBM system, the first step in the RM&D solutions is the data acquisition process. Conditioning monitoring data which can either be in the form of information from the lift controller such as fault signals and error codes or sensors data are acceptable. In this code, we did not attempt to define the list of conditioning parameters because there are several methods to obtain monitoring data and technologies may progress eventually and as such it would not be ideal to prescribe the specific monitoring points. From a regulatory and safety perspective, our approach would be to focus on defining the desired outcomes to be achieved by the RM&D solutions (this will be covered in more details in the monitoring outcomes later).

5 DATA PRE-PROCESSING

With a large amount of data being collected from the lifts, we learnt that there may be a need to pre-process the data before transmission to the cloud server to minimise the load on the network bandwidth. An example would be in the form of edge computing. That is to perform preliminary analysis on the data collected, segregating them based on the criticality of information and only transmit the data to the cloud that require urgent attention. It is included as a recommendation in the code because this is a desirable feature for the RM&D solutions.

6 DATA ANALYTICS

This is the most important step in the RM&D solutions where condition monitoring data are passed over to the central server i.e. cloud for analytics purposes. There are various models or techniques available to detect anomalies during the lift operations as well as to predict potential failures and future breakdowns of the lift. For example, model-based approach (construction of accurate model of the lift system) and/or data driven approach (use of artificial intelligence or machine learning algorithms) can be used to estimate the remaining useful life of the system or component before a fault or failure happens (Tung & Yang, 2009; Eisinger, 2021). However, for the code's purposes, we felt there was no need to specify the type of analytics approach that are acceptable. Instead, we choose to specify the "monitoring outcomes" or the desired outcomes that ought to be fulfilled by the RM&D solutions.

6.1 Monitoring Outcomes

In deriving these outcomes to be achieved by the RM&D solutions, a Failure Mode and Effects Analysis (FMEA) is being used. FMEA is a methodology used at design stage to analyse the possible points of failure in a system, product or process and the impact of that failure. This method is suitable because the same reasoning used for identification of component or system failures at design can also be applied similarly for the downstream RM&D solutions since they are designed to diagnose lift issues and prevent lift breakdowns before they occur.

The first step of the design FMEA is to identify the "item" which is the subsystem or component. The list of principal components or subsystems are generated using various references and our understanding of lift technology (The Chartered Institute of Building Services Engineers, 2020; Andrew & Kaczmarczyk, 2011; Janovsky, 2017). Next, we then list down the function, failure mode and the effect of the failure on the user or system. Failure occurrence and detection were excluded from the FMEA matrix. The former was due to the lack of comprehensive data for all the subsystem or component. Furthermore, the failure probability is also dependent on many variables such as environment, material use, usage and design. The latter is not meaningful as the purpose of RM&D solutions is to help in enhancing failure detection. Thus, the focus of the FMEA will be primarily on the severity of the failure if it occurs. Items high on the severity index should be monitored and diagnosed. Once these are done, we then rank each failure mode, based on the criteria from a severity level as shown in Table 1. In this FMEA, we not only consider the safety aspect, but also consider operational reliability when deciding the severity. For example, it is a well-established fact that doors are often the biggest contributor to lift breakdown. 30% or more of the breakdowns in a lift are due to door issues (Park & Yang, 2010). Therefore, the door systems are assigned a score that is high on the scale. Table *2* shows the severity level used for this FMEA.

After the severity values are assigned, we then apply a cut off level of 5 to decide the items for the monitoring outcomes. The final list of monitoring outcomes can be found in

*Table **3***.

Another requirement of the data analytic section is to necessitate the provision of output of the data analysis. System recommendations need to be provided to maintenance personnel to carry out part replacement, repair, or maintenance on the lift before a breakdown occurs. They can either be immediate in nature if breakdown or fault is imminent or scheduled to be carried out in the coming days or during the next planned maintenance for issues that are less critical. This will help to provide maintenance companies with greater operational flexibility and better optimisation of their manpower deployment.

Last but not least, the requirement to provide feedback into the IoT platform to improve the accuracies of the data analytics model is also included because this is an important feature to help the RM&D solutions to refine the accuracy of future diagnostics and be increasingly effective in the long run.

7 DATA VISUALISATION

The code also included the requirements for data visualisation platform to be included as part of the RM&D services. The rationale for this is transparency – by having information on the performance and status of the assets readily available to the lift owners. This could be done via a web-based interface and/or mobile application which helps to provide the flexibility and accessibility for lift owners to have a better overview of the equipment status. There is also a list of specifications recommended to be included in the data visualisation such as lift manufacturer, lift speed, rated capacity etc.

8 REMOTE INTERVENTION AND CYBERSECURITY

At the end of the code, we included two sections on remote intervention and cybersecurity. The first is because we are aware that there are systems out there which are capable of remote intervention to minimize mantraps and reduce rescue duration. This is not specifically prohibited as long as such function does not interfere with the safety of the lift nor compromise the safety of the users who are using the lifts. The section on cybersecurity was written with the intent to address the vulnerability of RM&D to cyberattacks and compromising the safety of the lifts. While we understand that there are number of cybersecurity standards around, ISA/IEC 62443 (Industrial network and system security) is the most applicable for RM&D solutions. Also, a new cybersecurity standard for lifts and escalators, ISO 8102-20 (Electrical requirements for lifts, escalators and moving walks – Part 20: Cybersecurity) is currently under development and takes reference from the IEC 62443. Hence, it is more than appropriate for RM&D solutions to meet IEC 62443 for cybersecurity standards in the interim and eventually to follow ISO 8102 once it is released.

Table 1: FMEA of Monitoring Outcomes of RM&D Solutions

S/N	Item	Function	Failure Mode	Effect	Severity	Critical for RM&D solutions
1	Traction Machine	Provide power to move the lift car up and down the shaft.	Overheating, bearing fault or short circuit etc leading to functional loss	Lift cannot move - breakdown	7	Yes

2	Brakes	Electro-mechanical devices capable of stopping the lift car when required.	Malfunctioning due restriction in movement or failure to engage	Injuries, or death due to overspeed of lift car	9	Yes
3	Controller	The brain of the lift system necessary to control and monitor the operation of lift.	Printed Circuit failure, loose connection, short circuit etc	Lift cannot move - breakdown	7	Yes
4	Suspension Ropes	Wire rope used to raise and lower the lift car	Wire rope breakage	Plunging of lift car	9	Yes
5	Car	Part of the lift that carries the users and/or other loads	Dents or damages caused by objects hitting the wall	Loss of aesthetics appeal	3	No
6	Alarm Bell	A device used for calling of attention and assistance	Loose connection or speaker failure	Unable to call for help when required	2	No
7	Intercom	A device used for communication between the user in the car and maintenance personnel	Loose connection, microphone and speaker failure	Unable to communicate with rescue team when required	2	No
8	Car and Landing Door	A means for users to enter and exit the lift car when the lift car is at the landings and protect users from entering the lift shaft when lift car is not at the landings	• Interlock failure – car move while doors are open • Dents or damage to door panels	• Injury or death due to crushing of passengers or falling of users into the lift shaft • Breakdown	9	Yes
9	Overspeed Governor System	Safety device to stop the lift car in the event of descending car or when the lift exceeds a predetermined speed	• Excessive Elongation of ropes • Malfunctioning of governor mechanism	Fail to hold the governor rope to trigger the safety gear	9	Yes
10	Guide System (guide rails, guide shoes and roller guides)	Help the lift car to maintain its travel in the vertical direction. Affects ride quality as well.	Wear and tear of the guide system	Affect ride quality	7	Yes
11	Safety Gear	Safety device used to grip the guide rail in the event of uncontrolled descent of the car due to breakage of suspension ropes	Malfunctioning of governor mechanism	Plunging of lift car	9	Yes
12	Signal Fixtures (buttons and indicators)	Used for the hall and car calling purpose and indication of the lift position.	Malfunction caused by vandalism or overuse	Inconvenience to the users	3	No

13	Levelling Devices	To move the lift car, when it is the door zone, at a reduced speed and eventually stop at the landing	Misaligned levelling devices, malfunction levelling switches etc	Mis-levelling of lift car at landings leading to trips and fall	7	Yes
14	Buffers	Resilient stop at the end of travel, and comprising a means of braking	Oil leakage, aging polyurethane buffer, cracked or corroded spring	Fail to arrest the free fall of the lift car in the event it happens	7	Yes
15	Travelling Cable	To provide electrical connection to lift car	Loose connection or cable breakage	No power in the lift car, inconvenience to users	3	No
16	Compensation system	To reduce power requirement for the traction machine and ensuring sufficient traction	Compensation chain/wire rope breakage	Increased power requirement and affects traction	6	Yes
17	Emergency backup power supply	To provide backup power to the lift system in the event of power supply	Batteries failure	No power for the lift system during power failure, inconvenience to users	2	No

Table 2: Severity Scale for FMEA

Severity of Effect	
10	May result in safety issue or regulatory violation without warning
9	May result in safety issue or regulatory violation with warning
8	Primary function is lost or seriously degraded
7	Primary function is reduced and customer is impacted
6	Secondary function is lost or seriously degraded
5	Secondary function is reduced and customer is impacted
4	Loss of function or appearance such that most customers would return product or stop using service
3	Loss of function or appearance that is noticed by customers but would not result in a return or loss of service
2	Loss of function or appearance that is unlikely to be noticed by customers and would not result in a return or loss of service
1	Little to no impact

Table 3: List of Monitoring Outcomes

Lift system and their sub-system	Monitoring Outcomes
1. Traction Machine	Provide recommendation on possible rectification works for the traction machine and indicate when they are required.
2. Brakes	Provide recommendation on possible rectification works for the brakes and indicate when they are required.
3. Suspension Means	Provide recommendations on possible rectification works for the suspension means and indicate when they are required.
4. Guide system (i.e. guide rail and guide shoes or rollers)	Provide recommendations on the possible rectifications for the guide system and indicate when they are required.
5. Car and Landing Doors (including door protective devices)	Provide recommendations on possible rectification works for the car and/or landing door system and indicate when they are required.
6. Levelling Devices	Provide recommendations on possible rectification works for potential occurrences and instances of mis-levelling and indicate when they are required.
7. Fault Diagnosis including the following components: a) Overspeed Governor b) Safety Gear c) Controller and Inverter Drive d) Buffer e) Compensation System	Indicate if one or more of the following fault(s) is/are possible cause(s) for the stoppage of the lift: • Overspeed Governor Activation • Safety Gear Activation • Controller and Inverter Drive Failure • Buffer Activation • Compensation System Activation • Ascending Car Overspeed Protection Activation • Unintended Car Movement Protection Activation • Fire Emergency • Power Failure

9 PERFORMANCE INDICATORS

In the Annex of the code, we define the performance indicators to evaluate the effectiveness of the RM&D solutions. There are a total of seven performance indicators as shown in Table 4. These indicators aim to objectively measure the performance of the RM&D solutions in 2 main areas: the performance of the lift as well as productivity indicators and to provide a harmonized method of evaluating across the different types of RM&D solutions in the market. We will look at some of these indicators in detail.

9.1 Average Uptime

Common to all industrial systems and processes, the availability of the equipment is a key indicator of reliability. Any equipment downtime would result in loss of production and all operators would like to maximise the uptime of their equipment. Therefore, availability is a factor of MTBF, also known as mean time between failures, and MTTR, or mean time to repair (Torell & Avelar, 2004). As mentioned earlier, one advantage of having RM&D is proactive maintenance resulting in greater equipment availability. Therefore, the average uptime of the lift provides an indication of the effectiveness of the RM&D solutions. At this juncture, we would like to highlight that the uptime formula is calculated without the inclusion of planned maintenance downtime. There are two reasons for this. Firstly, such maintenance is usually performed when the lift is not required to be functional. Secondly, maintenance contractors would be discouraged to carry out pre-emptive maintenance if this time is included in determining the performance of the RM&D.

9.2 Diagnostics Accuracy

A confusion matrix consisting of parameters such as true positives, false negatives, false positives and true negatives is often used to evaluate the effectiveness of the analytics engine. There are inherent difficulties in determining whether a positive prediction is true or false. Unless the predicted fault is not rectified and left for it to manifest, it will be difficult to confirm if the positive prediction is indeed true or false. Hence, we focus only on recommendation as a mean of assessing if the RM&D solutions are accurate in its prediction. A true intervention case is where the RM&D solutions recommend a visit to the lift location and the prediction matches the fault or failure on site.

Table 4: List of Performance Indicators

S/N	Indicators	Formula
1	Technical Fault per Equipment (TFE)	$\frac{\text{Total Number of Technical Faults}^{3}}{\text{Total Number of Equipment}}$
2	Fault per Equipment (FPE)	$\frac{\text{Total Number of Faults}^{4}}{\text{Total Number of Equipment}}$
3	First Time Fix Rate (FTFR)[5]	$1 - \frac{\text{Total Number of the Repeated Technical Faults}}{\text{Total Number of Technical Failures}}$
4	Mean Time To Repair (MTTR)[6]	$\frac{\text{Total Downtime of Technical Faults}^{7}}{\text{Total Number of Technical Faults}}$
5	Average Monthly Uptime (UT)	$\frac{\text{Maximum Possible Running Hours - Total Downtime of Technical Faults}}{\text{Maximum Possible Running Hours}^{8}}$
6	Diagnostics Accuracy (DiA)	$\frac{\text{Total Number of Intervention Cases marked as True (T)}^{9}}{\text{Total Number of Intervention Cases}^{10}}$
7	RM&D Device Availability	$\frac{\text{Total Number of RM\&D Units That Are Online}}{\text{Total Number of RM\&D Units}}$

[3] A list of technical faults is given in Annex A
[4] Faults is sum of technical faults and non-technical faults. A list of non-technical faults is given in Annex A.
[5] Technical failures that happen within the next 30 days after they have been rectified are to be considered for the calculations.
[6] MTTR exclude the following: (1) major repair/overhaul that takes more than 1 day (refer to the list of exclusion cases in Annex B; (2) waiting time for spare parts arrival; and (3) additional time needed to do hot-testing.
[7] Total downtime of technical faults is the sum of all time spent to rectify all technical faults in hours.
[8] Maximum possible running hours is the number of days in the month multiplied by 24 hours for each lift.
[9] A True (T) Intervention Case is when the RM&D prediction matches diagnosis/faulty component on site.
[10] Intervention cases are defined as cases prompted by RM&D solutions whereby a visit to lift by maintenance personnel is required.

10 TRIALS

These trials were conducted on 174 lifts with RM&D solutions from lift manufacturers European OEMs and sensors based IoT solution providers (3rd party solution providers). The lifts were located across Singapore, and they cover offices and light industrial use.

The focus of the trials would be on the proof of concept of the RM&D solution. The solution would be tested on whether lift faults can be accurately picked up, diagnosed and predicted under a monthly maintenance regime. It also aims to provide the technician an opportunity to be familiar with the technology and its usage. One example would be for the technicians to provide feedback on system-generated diagnostics which would help close the machine learning loop and refine the accuracy of future diagnostics. This is particularly important for 3rd party solution providers because an effective feedback loop between the 3rd party solution provider and the maintenance company is essential to improve the accuracy of fault predictions. This phase therefore also allows the owner to understand the dynamics of this relationship and learn how to manage the coordination effectively in the future.

The results have been promising so far. We have also seen improvements in some of the indicators. For example, there was an improvement of about 2% for the Average Monthly Uptime and decrease in Failure per Equipment from a value of 0.2. Details of the results of the performance indicators can be found in Table 5.

Table 5: Results from Local Trials

Performance Indicators (per lift/month)	Values
Average Monthly Uptime (UT)	99.5~99.7%
Faults per Equipment (FPE)	0.06~0.09
Technical Faults per Equipment (TFPE)	0.05~0.08
First Time Fix Rate (FTTR)	89~93 %
Mean Time to Repair (MTTR)	16 ~19%
Diagnostics Accuracy (DiA)	85~94%
RM&D Device Availability	96~99%

11 MOVING FORWARD

The trials have provided validation on the improvements in lift performance and safety with assessment based on the code. Further trials would have to be conducted with the use of the code to gain more insights into the impact of RM&D solutions with reduced maintenance frequency (once every 3 months or more) on the performance and safety of lifts.

12 CONCLUSIONS

In this paper, we briefly describe the code of practice for RM&D solutions developed for usage in Singapore and some of their considerations. The code covers the following key areas: (i) Data Acquisition (ii) Data Pre-processing (iii) Data Analytics (iv) Data Visualisation (v) Remote Intervention and (vi) Cybersecurity. For data acquisition, there is no specified list of monitoring parameters. Instead, we introduce the concept of monitoring outcomes which aims to define the desired outcomes to be achieved by any RM&D solutions. There is also a growing concern with such system on whether cyberattacks may compromise safety of the lift and users Therefore, the code has a section on remote intervention and cybersecurity.

At the end of the code, an informative annex on performance indicators is provided. A total of 7 performance indicators is listed down which aims to allow us to evaluate the effectiveness of various RM&D solutions in the market. Using them, we can quantify the outcome of local trials of RM&D solutions in Singapore and based on these indicators, we assess those RM&D solutions have been effective so far. This will provide us further confidence to continue to pursue the CBM and PdM approach with the use of RM&D solutions to achieve a more productive workforce.

REFERENCES

Amazon Web Services, 2022. *What is IoT?.* [Online]
Available at: https://aws.amazon.com/what-is/iot/
[Accessed 15 4 2022].

Andrew, P. & Kaczmarczyk, S., 2011. *System Engineering of Elevators.* s.l.:Elevator World Inc.

Beebe, J., 2016. Integration of Lift Systems into the Internet of Things and the Need for an Open Standard Information Model. *6th Symposium on Lift & Escalator Technologies.*

Bourgeat, J.-P., 2018. 24/7 Connected Service: Improving the Flow of Urban Life. *International Elevator & Escalator Symposium*, 15-16 November, pp. 27-34.

Eisinger, S., 2021. *Prognostic maintenance: seeing into the future.* [Online]
Available at: https://www.dnv.com/to2030/technology/prognostic-maintenance-seeing-into-the-future.html
[Accessed 2 March 2022].

Janelle, P., 2018. *Predictive Maintenance and Beyond: The Top 10 Ways IoT is Changing Elevators,* s.l.: Buildings.

Janovsky, L., 2017. *Elevator Mechanical Design.* 3rd ed. s.l.:Elevator World, Inc.

Lai, C. T. A., Jiang, W. & Jackson, P. R., 2019. Internet of Things enabling condition-based maintenance in elevators service. *Journal of Quality in Maintenance Engineering,* 25(4), pp. 563-588.

Lin, Y., Hsu, A. & Rajamani, R., 2002. A Simulation Model for Field Service with Condtion-Based Maintenance. *Proceedings of the 2002 Winter Simulation Conference,* Volume 2, pp. 1885-1890.

Oracle, 2022. *What is IoT?.* [Online]
Available at: https://www.oracle.com/sg/internet-of-things/what-is-iot/
[Accessed 14 April 2022].

Park, S.-T. & Yang, B.-s., 2010. An Implementation of risk-based inspection for elevator maintenance. *Journal of Mechanical Science and Technology,* 24(12), pp. 2367-2376.

Schiller, M. & Falge, C., 2018. Connecting Equipment, Customers and Passengers: The Internet of Elevator & Escalator. *International Elevator & Escalator Symposium,* 15-16 November, pp. 105-112.

Schmidt, B., Sandberg, U. & Wang, L., 2014. *Next Generation Condition Based Predictive Maintenance,* s.l.: s.n.

Smith, R., 2020. IOT, Magic or Myth?. *11th Symposium on Lift and Escalator Technologies.*

The Chartered Institute of Building Services Engineers, 2020. *CIBSE Guide D, Transportation Systems in Buildings,* s.l.: CIBSE.

Torell, W. & Avelar, V., 2004. *Mean Time Between Failure: Explanation and Standards,* s.l.: Schneider Electric – Data Center Science Center.

Tung, T. V. & Yang, B.-S., 2009. Machine Fault Diagnosis and Prognosis: The State of The Art. *International Journal of Fluid Machinery and Systems,* Volume 2, pp. 61-71.

Yarmoluk, D. & Mitchell, A., 2019. *Why move from condition monitoring to predictive maintenance? - Part 1.* [Online]
Available at: https://www.ibm.com/blogs/internet-of-things/iot-condition-monitoring-part-one/
[Accessed 15 April 2022].

ANNEX A – LIST OF TECHNICAL FAULTS AND NON-TECHNICAL FAULTS

S/N	**Technical Faults**	**Non-Technical Faults**
1	Motor [Thermal/Voltage/Current]	Noise
2	Machine brake [Brake Switch]	Display Indicators/LCD
3	Electrical Components [Switches/Contactors/Relays/PCBs]	Faulty buttons [Car/Landing]
4	Main Drive Unit/Frequency Inverter	Card reader
5	Landing Doors	External Element Blocking Doors [Object/Human]
6	Car Door	Car Interior [False Ceiling/Cladding]
7	Buffers	Fire Homing/Power Failure Mode
8	Speed Control System [Shaft/Motor Encoder]	Natural Disaster/Incident leading to component failure [Water ingress]
9	Overspeed Governor & Governor Rope	Oil Pots Leakage
10	Levelling Accuracy	
11	ACOP/UCMP/Rope gripper	
12	Batteries Failures [ARD/EBOPS]	
13	Suspension Ropes	
14	Bearings Worn-out	
15	Load Measuring Devices [Overload Signal]	
16	Compensation Devices [Chain/Rope] –	

ANNEX B – LIST OF EXCLUSION

S/N	Examples of Special Events (non-exhaustive)
1	Hoisting motor replacement/repair
2	Ropes replacement
3	Main/Diverting sheave replacement/repair
4	Major lift components, e.g. governor, safety gear
5	Total failure of Frequency Inverter
6	Water ingress situation
7	Building power failure

BIOGRAPHICAL DETAILS

Mr Hashim Bin Mansoor is the Director of Engineering and Technology Department (ETD), Building and Construction Authority (BCA), Singapore. He is a professional engineer in mechanical engineering and Specialist Professional Engineer in the fields of lift & escalator. As the Director of Engineering and Technology Department, he is responsible in looking at innovations and digital improvements that can be made to further improve the safety and reliability of lifts and escalators.

Mr Justin Tai is currently the Director of Regulation and Process Transformation Department (RPTD) at BCA, which has regulatory oversight of amusement rides, lifts, and escalators. His professional experience includes performing design reviews and conducting investigations involving amusement rides, lifts, and escalators as well as contributing to the education and safety committees on vertical transportation in Singapore.

Mr Yao Hui Chee is currently a Senior Engineer in ETD at BCA with about 10 years of experience in lift and escalator. Beside actively involving himself in inspections and investigations of lifts, escalators and amusement rides in Singapore, he also represents BCA as a member of the Working Group on Lifts, Escalator and Passenger Conveyors, which is involved in regular review of the prevailing standards for lifts and escalators. He is currently pursuing an MSc in Lift Engineering with University of Northampton and is in the final year of his studies.

Mr Kenneth Ong is currently a Senior Engineer in ETD at BCA. His experience includes performing design reviews, inspections and investigations involving lifts, escalators and amusement rides in Singapore. He was working in the oil and gas industry for 13 years before joining BCA 2 years ago.

Mr Yih Perng Khoo is an Executive Engineer in Investigation and Enforcement Department (InED) at BCA. During his three years tenure in BCA, he performed regulatory works, design reviews, inspections and investigations involving amusement rides, lifts, and escalators. Prior to joining BCA, he was in the rail transport industry for 2 years.

Ms Jody Tan is a Senior Engineer in InED at BCA and has been in the L&E industry since year 1997. She evaluates and reviews design and conformance to safety standards of lift, escalator, and amusement ride in Singapore. She participates in incident investigation that involves lift, escalator, and amusement ride in Singapore.

Mr Andy Goh is currently an Executive Engineer with BCA, which regulates the amusement rides, lifts, and escalators in Singapore. His professional experience includes conducting incident investigations & inspections for lifts and escalators. He is actively involved in the development of lifts' Remote Monitoring & Diagnostics (RM&D) scene in Singapore.

The Technical Challenges Involved in Lifting 40 Tonne Trucks Using Rigid Chain Technology in a Confined Space

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Keywords: Rigid-chain, RCT, Truck lift, Theatre lift, Lorry lift, Vehicle lift, Truck elevator

Abstract. This paper will describe the technical challenges involved in installing two 40 Tonne truck lifts in a theatre whilst utilising rigid chain technology (RCT) in a confined space. RCT is based on single interlinking chains comprised of single links. These links lock together when the chain is deployed, creating a rigid propelling column which when designed for the lift industry, means it is possible to design a lift which can transfer loads of up to several hundred tonnes.

It will explain how the project was procured from a consultancy perspective after the basic design of the building and lift shaft had been finalised, and on how reviewing the truck lift information, it became apparent that the design was incomplete and appeared impractical.

Areas examined include the applicable standards, anticipated loads to be lifted and evaluation of the various options for the truck lift design. It will include the results of the research that was undertaken whilst exploring the technology, energy efficiency, safety of the lifting systems and comparison sites where similar operational requirements had been used resulting in the decision to recommend RCT technology.

Illustrations of the challenges that were overcome during the design and installation process are included.

1 INTRODUCTION

This paper explains how the project was procured from a consultancy perspective after the basic design of the building and lift shaft had been finalised, and on how reviewing the truck lift information, it became apparent that the design was incomplete and appeared impractical.

The study looks at a number of areas including the applicable standards, anticipated loads to be lifted and evaluation of the various options for the truck lift design.

2 CLIENT REQUIREMENTS

The client, a major city council, decided to enhance their city's cultural appeal by planning to build a combined 1,700-seat theatre and 5,000-person auditorium on the same site. The proposed brownfield site straddled a road; therefore, the building was designed to have the theatre stage and auditorium on the same floor level, this floor level or performance level, (level 2) is 6.66m above road level (level 0).

The building was split into the areas shown below: (see fig. 1)

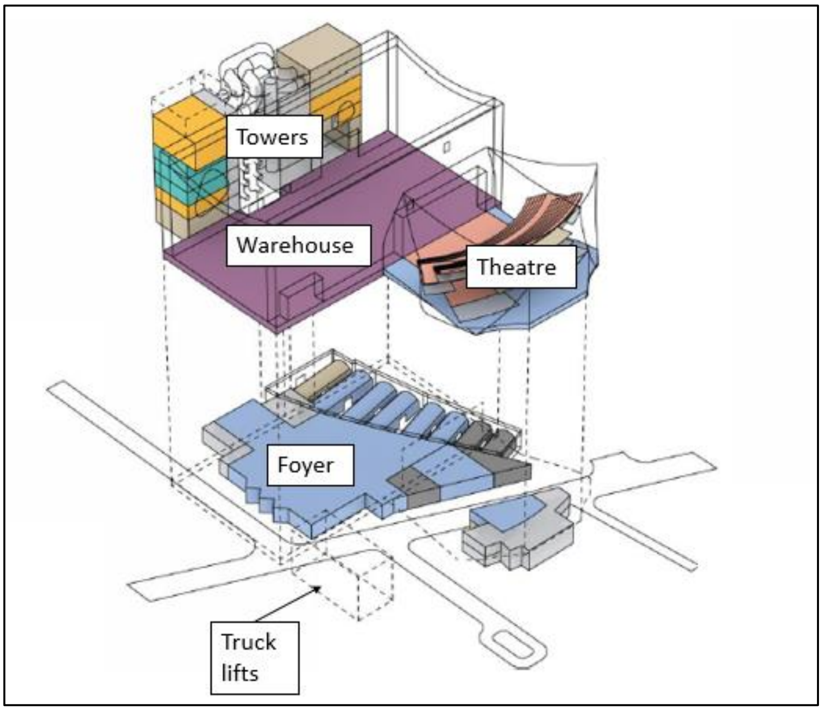

Figure 1 Layout of the building

To move trucks and equipment from road entrance level (level 0) up to the performance level (level 2) two truck lifts were proposed.

3 INITIAL CLIENT REQUIREMENTS

At the request of the client, a 'Sense Check' review was carried out on the finalised basic design of the building and shafts. Our review concluded that many areas of the design and operation were either incomplete, unworkable or impractical.

The 'Sense Check' covered the following areas:

A. The size of truck/trucks to be carried

B. The number of trucks to be moved per event

C. The method of loading and unloading the trucks into and out of the lift

D. The size of oversize production equipment and sets

E. The security of high value loads on the trucks

F. Whether the truck drivers could stay in their cabs or not

The results of initial 'Sense Check' report:

A. The size of truck/trucks to be carried:

It was established that the maximum truck size and weight allowed on UK roads as per UK and EU legislation was 16.5m length x 2.55m width x 4.4m height. A gross weight of 44 tonnes is permitted on UK roads however following discussion with the client a gross weight limit of 40 tonnes was applied as a maximum weight capacity of the lifts.

B. The number of trucks to be moved per event:

Research was carried out into the typical number of trucks used for a performance in a large warehouse space and with the assistance of the theatre operational team, the number of trucks to be moved for a performance was established at 20 trucks.

C. The method of loading and unloading the trucks into and out of the lift:

The client required the trucks to be able to drive directly onto the performance level floor which as previously discussed is 6.6m above the access road. In addition, the client required the facility to off load trucks from the rear of the trailers, using a system to provide an adjustable level access to the trailers (dock levelling position).

A tracking exercise was carried out by a specialist vehicle movement consultant, and they calculated that the trucks entering from the street would foul the entrance wall (A) or roller shutter guide (B) on the lift entrance. (See fig. 2)

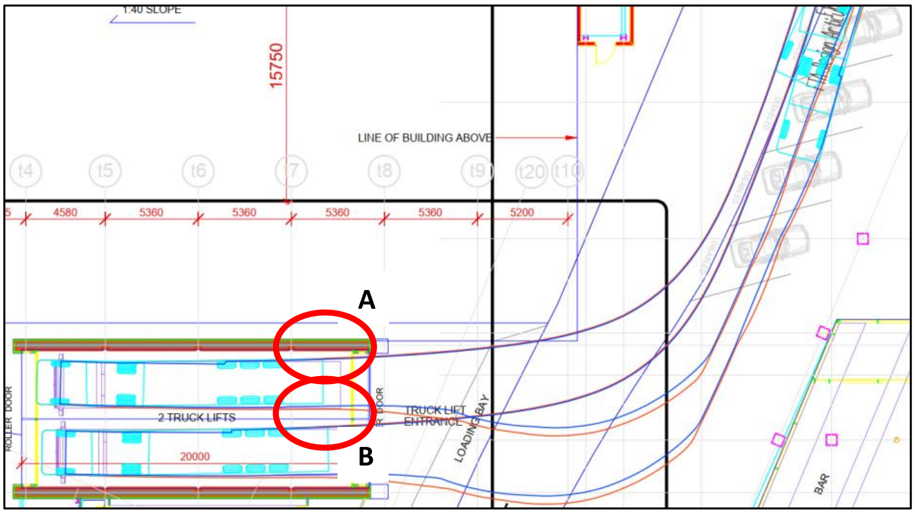

Figure 2 Truck tracking into the lift from the street

At the west end of the lifts there is a turning area (the Square), and the same exercise was carried out to establish the viability of trucks entering the lift from the Square. (See fig.3)

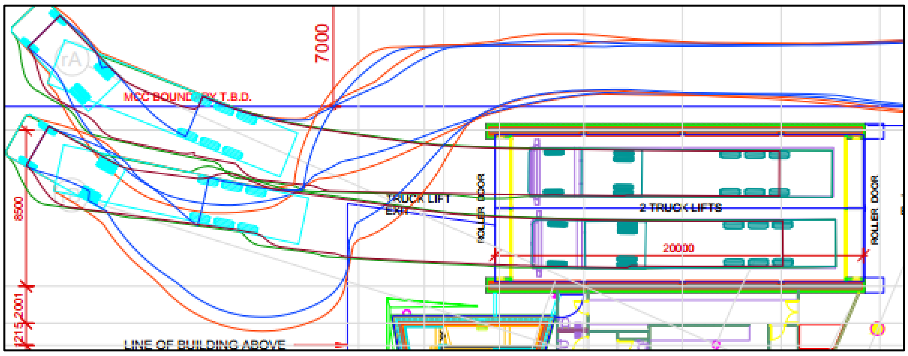

Figure 3 Truck tracking from the square

The tracking exercise established that the only feasible way for trucks to access the lifts was from the Square, by them reversing into the lifts as shown in the drawing extract above.

D. The size of oversize production equipment and sets:

The client's theatrical production staff were consulted on the typical maximum size of oversize production equipment, and it was confirmed that the equipment would be smaller than the proposed platform that would accommodate a 16.5m long truck. It was stipulated to the production staff that loads must not be allowed to lean on the side walls of the lift as they were not designed for any loads to contact them.

E. The security of high value loads on the trucks:

The client required high value loads to be unloaded from trucks at the dock levelling position without the trailer doors being opened outside of the building. To accomplish this the trucks had to be able to reverse onto the level 2 loading bay and open the trailer doors. The drawing extract (see fig. 4) shows the tracking required to achieve this and demonstrated it was achievable.

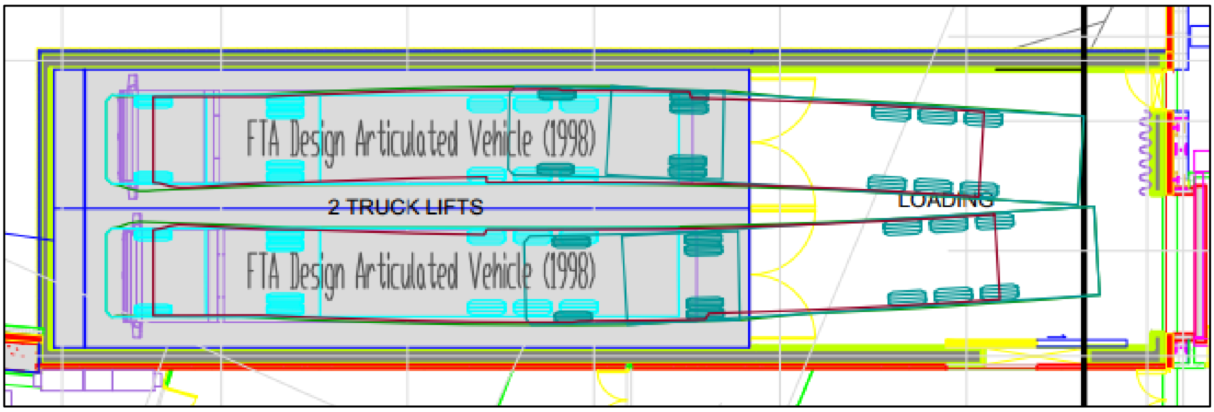

Figure 4 Tracking inside the lift.

F. Whether the truck drivers could stay in their cabs or not:

The initial designs for the theatre showed a staircase located adjacent to the truck lifts, however, this was removed from the scheme prior to our involvement. With the removal of the staircase the route for drivers and lift users to travel from the ground floor to level 2 without using the truck lift was convoluted. Further to this was the associated risk of getting lost or entering restricted areas whilst walking through the theatre.

The various regulations and standards were reviewed, and it was concluded that it would be acceptable for persons to travel on the lift platform if the necessary precautions and safeguarding features were installed, these features and precautions included:

- Installing controls on the lift platform to enable lift users to open the landing doors at floor level
- Defining the truck lift operation e.g., truck engine turned off when in position on the platform
- Ensuring there was minimal risk of fire on the truck during lift operation
- Providing a means of contacting rescue services in the case of lift malfunction or emergency, including means of communication (emergency and normal)
- Preparing a Personal Emergency Evacuation Plan (PEEP) for all personnel using the lift
- Providing a means for truck drivers to leave the lift when it was positioned at dock levelling position
- Other measures to ensure persons using the lift would be safe

A report was compiled with the above issues highlighted and proposed solutions, this was accepted by the client.

4 DESIGN DEVELOPMENT

The following areas and issues were reviewed to complete the design and installation of the truck lifts:

4.1 Researching and understanding the rigid chain technology

Rigid Chain Technology (RCT) is based on single interlinking chains comprised of single links. These links lock together when the chain is deployed, creating a rigid propelling column which, when designed for the lift industry, means it is possible to design a lift which can transfer loads of up to several hundred tonnes.

To ensure rigid chain technology was suitable for this truck lift application the following research was carried out.

The lifting systems reviewed:

- Hydraulic scissor lift (see Fig. 5)

Figure 5 Hydraulic scissor lift

- Rigid Chain System (RCS) – Serapid Ltd [1], (see fig. 6)

Figure 6 Underneath rigid chain system (during construction)

The results noted on site visits to a scissor lift and rigid chain lift and other research were as follows: (see table 1)

Table 1 Results of comparison between systems

	Hydraulic scissor lift	**Rigid chain system**
Space required for power pack	Large space required. Approx. space required 40m² x 4m².	No space required outside lift shaft.
Space required for control equipment.	Space adjacent to the lift shaft approx. 30m² x 3m high	Space adjacent to the lift shaft approx. 30m² x 3m high
Complexity of system.	Whole system operates at high pressure which creates higher likelihood of failure e.g. hydraulic hoses had been replaced on the scissor lifts visited on our evaluation exercise and the unit was less than 5 years old!	This system comprises of simple motor, gearbox and rigid chain arrangement; gearboxes, prop shafts, chain sprockets and rigid chain are all well understood technologies.
Dock levelling facility	The requirement to be able to ‘inch’ the lift for dock levelling would be problematical due to response of hydraulics.	The main motors have a variable voltage variable frequency drive and the ‘inching’ operation is easily accommodated.

Cooling equipment.	Air blast oil cooler mounted outside motor room of refrigerated oil cooler with external condensers.	Integral fan on the main motors.
Noise of system	Pump units very noisy and air blast oil cooler very noisy.	Minimal noise from main motors.
Maintenance	High levels of maintenance on hydraulic pump system.	Low maintenance requirement on entire system.
Cost of lift	Higher than RCS (commercially sensitive information)	Lowest price (commercially sensitive information)

The results above showed that the rigid chain lift had many advantages over the scissor lift. The scissor lift was ultimately discounted for the following reasons

- The project did not have an area large enough that could be used for housing the required hydraulic power units,
- The noise of the required oil coolers would be a serious issue due to close proximity of residential buildings,
- the cost of the scissor lift was higher than the rigid chain system,
- the 'inching' facility required for dock levelling operation would be difficult to achieve with the scissor lift.

To confirm that the rigid chain system met the client's requirements regarding noise, and to satisfy ourselves that the product was suitable for truck lift applications, site visits were arranged to a truck lift installation in Riga, Latvia and the Serapid [1] factory in Dieppe, France. Noise readings were taken during the site visit and were deemed satisfactory, and the factory visit met requirements.

4.2 Developing the truck lift design to suit the structural openings provided in the base build and later structural changes

The size of the lift shaft was 8m wide x 20m long (for both truck lifts) and was set during the planning stage of the project. There was no opportunity to increase it due to planning constraints and site limitations. The original design of the truck lift had manual swing gates both on the lift car and landings with additional security shutters on each end of the ground floor landings. These manual gates were impractical due to the number of staff required to operate them and the space required on the landings; it also precluded the dock levelling facility required by the client. The design was changed to have power operated shutter doors as the ground floor landing doors and an infrared curtain on the lift car. This automated the lift operation at the ground floor and maintained the area of the lift for the truck usage. On the upper level the manual gates were an issue and the design changed to a powered rising barrier which automated the operation on level 2 (theatre and performance level). During the design development and construction phase of the project, several structural design changes impacted the truck lift design, including restrictions on the ground floor roller shutter door motors not being allowed outside the building outside walls, circled in red. (See Fig. 7)

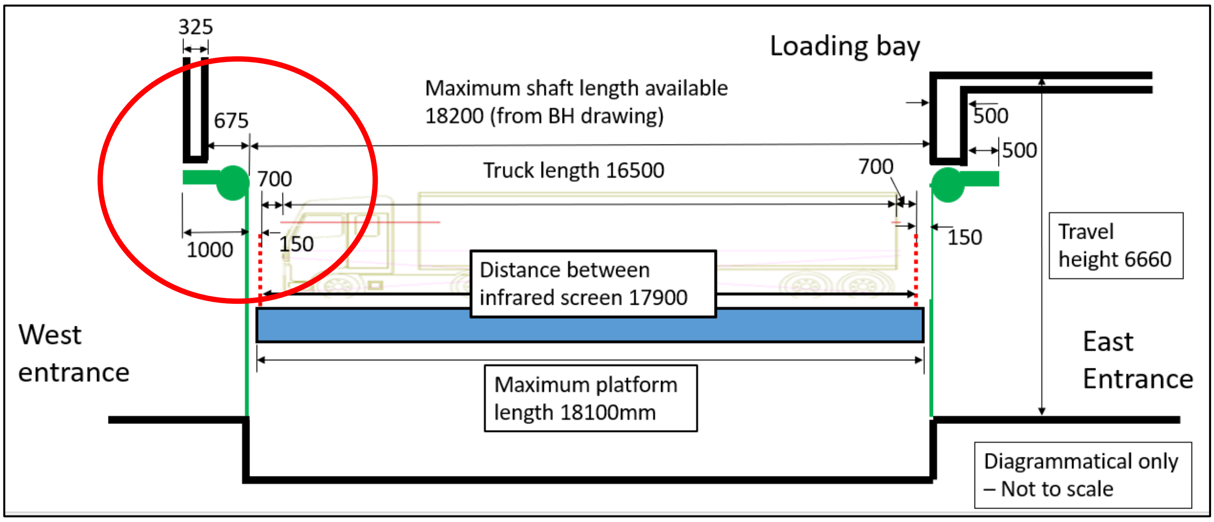

Figure 7 Ground floor roller shutter door motor issue.

Another structural change occurred with the rising barrier on level 2 being mounted on the face of the level 2 slab, this reduced the lift platform by 300mm.

4.3 Regulations, standards and codes the truck lifts must comply with

The overall lift is designed to comply with the Machinery Directive [2] and will operate at 0.075 m/second which is less than the Machinery Directive maximum operating speed of 0.15 m/second and will also comply with the British Standards regarding:

- Emergency communications – BS EN 81-28 [3],
- Safe working on lifts – BS 7255 [4],
- British Standard for new lifts complying with the Lift Directive – BS EN 81-20 [5] – where applicable. These areas included:
  - Safe operation and maintenance of the lift,
  - Features to enhance the passenger safety

4.4 Developing the method of operation including understanding truck tracking and manoeuvring

As previously described, the tracking of truck access to the lift was modelled by a specialist consultant. During the design development we were reviewing the tracking with every change in the design to maintain the usability of the truck lifts.

4.5 Liaising between the design team, client and truck lift manufacturer/installer and ensuring the truck lift design met the client’s expectations during the design development

We acted on the client’s behalf to ensure the functionality of the lifts and the requirement to move 40 tonne trucks was maintained. We frequently challenged changes in design that would affect the size of the lift.

One of the lifts has now been used to move a 40 tonne truck during construction operations (beneficial use).

4.6 Acting as the lift specialist adviser to the project

A lift company was originally leading the rigid chain design and installation, but this company decided to withdraw midway through the design of the project, so the installer (who also was the manufacturer of the platforms and controls) stepped up to lead the project. The installer had experience of a truck lift overseas but limited knowledge of UK lift standards and codes, so we are providing lift expertise, knowledge and guidance to the contractor.

4.7 Integrating the truck lifts operation with the fire strategy of the building

The fire strategy had been prepared by the fire engineering consultant and included the main riding function of the lift. During the development of the fire strategy the document was revised and the function of the driver staying in their cabs had been removed without reason. Meetings and discussions took place with the fire consultant, and we drew up a fire cause-and-effect table which identified operational measures that are required to check the vehicle for smoke or fire before entering the lift and what shall happen if a fire is detected whilst the lift is in travel. This cause-and-effect table demonstrated that the drivers were not at risk and was accepted by the fire consultants.

4.8 Developing the Personal Emergency Evacuation Plan (PEEP) for the truck occupants who would be staying in their cabs during the lift operation

As part of the requirement for the drivers to stay in their cabs, a Personal Emergency Evacuation Plan (PEEP) was developed, this involved:

- Identifying persons covered by this PEEP
- Identifying areas of safety/refuge
- Determining safe routes to a place of safety
- Names of anyone appointed to assist the person in an emergency
- Listing specialist equipment that may be necessary
- Identifying where staff training is needed
- Detailing when and how escape practise will take place

Once formulated, the PEEP was circulated to the design team and client for review and comment. There were no comments and the PEEP was adopted.

4.9 Developing the test and commissioning plan including the use of 40+ tonne test weights

The test and commissioning plan was developed to demonstrate to ourselves (representing the client) that the lift operated satisfactorily in normal and test conditions, these were:

- Contract load normal operation and emergency stop – 100% contract load – 40 tonnes
- 10% overload operation and emergency stop – 110% of contract load – 44 tonnes
- 25% overload – lift held on brakes – 125% of contract load – 50 tonnes

The test and commissioning plan is yet to be completed and includes:

- Review of completed test sheets
- Review of test instrumentation and calibration certificates
- Normal operation e.g., doors, etc.
- Current readings compared with test sheets
- Lift operation and levelling including dock levelling operation

A complete defect inspection will be carried out on each lift.

4 CONCLUSION

Rigid chain technology provides an excellent solution to applications such as truck lifts. It has the advantage of being very simple and quiet in operation.

Lessons learnt:

- Involvement in the project at an early stage is essential to avoid having to compromise the lift design to fit the available space
- The lift design company must have a full understanding of lift standards and codes
- The whole design team must sign up to the minimum lift platform size and size of vehicle to be moved

REFERENCES

[1] Serapid Ltd, The Counting House, Elm Farm Park, Great Green, Bury Saint Edmunds

[2] The Supply of Machinery (Safety) Regulations 2008 (Directive 2006/42/EC)

[3] BS EN 81-28: 2003 *Remote alarm on passenger and goods passenger lifts (London, BSI)*

[4] BS 7255: 2012 *Safe working on lifts (London, BSI)*

[5] BS EN 81-20: 2020 *Safety rules for the construction and installation of lifts – Lifts for the transport of persons - Passenger and goods passenger lifts (London, BSI)*

BIOGRAPHICAL DETAILS

Philip Pearson is the Managing Director of UK based lift and escalator consultants Pearson Consult Ltd. He has been in the lift and escalator industry since 1986 having previously been a building services engineer. Philip has experience of the lift industry from all aspects; from a client perspective – responsible for all lifts and escalators at a large department store group – forming and running a lift and escalator company, designing lifts and escalators for a lift manufacturer and 20 years as a lift and escalator consultant, the last 7 of which has been operating his own practice. Philip is an active member of CIBSE, this includes being committee member and Papers Chair for CIBSE West Midlands region, responsible for organising and delivering CPD to the region and nationally and member of the CIBSE Lift Group Executive Committee responsible for organising northern events.

Lift Energy Modelling for Green Building Design

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Keywords: lift, elevator, energy, environment, simulation, modelling, traffic.

Abstract. Lifts are a relatively minor concern when considering green buildings, yet increasingly they are becoming subject to scrutiny with the drive to net zero. The energy consumption of lifts is a major part of their environmental impact. To reduce that impact, first, we need to improve our understanding and modelling of lift energy consumption. Many attempts have been made to define ways of calculating lift energy consumption. Some are so simplistic that their results are of questionable value. Others are so sophisticated that their widespread application is unlikely other than to specific products. This paper addresses why lift energy modelling is complex and discusses the factors which are most significant. Models based on calculation and traffic simulation are considered. The modelling method proposed addresses the need for considering passenger demand and allows for simple measurement and verification.

1 INTRODUCTION

In 1994 Peters presented a paper at the CIBSE National Conference titled *Green Lifts?* [1] posing the questions, "is there such a thing as a green lift", and "can we design a lift system that delivers good passenger service at an acceptable cost while incurring minimum environmental impact?". At the time there was little interest, but today these questions seem far more relevant and important; although lifts are generally considered a minor contributor to the environmental impact of a building, they are increasingly subject to scrutiny.

The environmental impact of lifts is likely to become even more important as the world builds up, which, perhaps surprisingly is the recommendation of some of the environmental lobby. In "There is no planet B" [2] Berners-Lee writes "The ideal city is compact and easy to get around. The buildings are tall and generally close together".

2 THE ENVIRONMENTAL IMPACTS OF LIFTS

To assess the environmental impact of vertical transportation systems, we first need to have some measure of environmental burdens. A Life Cycle Assessment or Analysis (LCA) is defined as the systematic analysis of the potential environmental impacts of products or services during their entire life cycle. It considers components such as:

- resource extraction of materials for manufacture
- manufacture and installation
- use of the product
- re-cycling and re-use
- waste
- transportation at all stages

A lift LCA presented in 1994 [1] was based on a 4-car group installed in London with a 30-year life and one major refurbishment at 15 years. The analysis suggested that the dominating environmental burdens in the life of this hypothetical lift system were the non-renewable resources depleted, the waste created, and the emissions generated through the production of electricity for the operation of the lifts while in use.

In 2013, Lorente presented her thesis titled *Life Cycle Analysis and Energy Modelling of Lifts* [3]. An extract from her LCA discussion, *Environmental Impacts of Lifts* was presented at the Lift & Escalator Symposium in 2014 [4]. Lorente presents results for a category 3 (medium usage) lift which is reproduced in Figure 1. The Eco 99 scale is an attempt to weigh the importance of environmental impacts based on human health, ecosystem quality and resources [5]. The energy mix assumed is based on 2008 data.

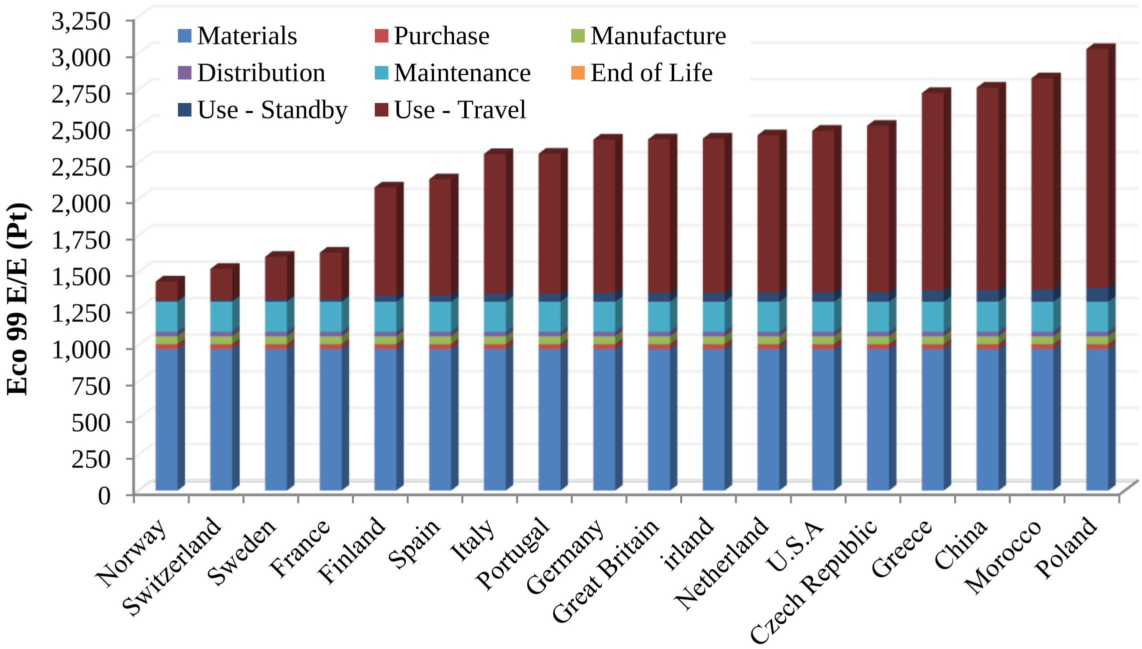

Figure 1 Environmental Impact results (630kg gearless traction) for the usage category 3, installed in different countries

Lorente states that the life expected for the lift and/or its components plays a decisive role in the final environmental impact of the lift. Indeed, for an occasionally used, economy lift with a short life, imported into a country with an “environmentally friendly” energy mix, the dominating environmental burdens are not going to arise from the electricity consumed in use. But they are still significant.

3 HOW A LIFT USES ENERGY IN SERVICE

3.1 The ideal scenario

Al-Sharif, Peters, and Smith [6] explain that in an ideal world, with no friction and losses, energy is never consumed by a lift, it is borrowed and then returned. Consider the morning in an office building with a full car travelling up from the ground floor. Part of the electrical energy supplied is converted into kinetic energy as the lift accelerates and is given back when the lift decelerates. The other part is given to the passengers as potential energy, see Figure 2. The potential energy is returned when the passengers travel back to the ground floor, see Figure 3.

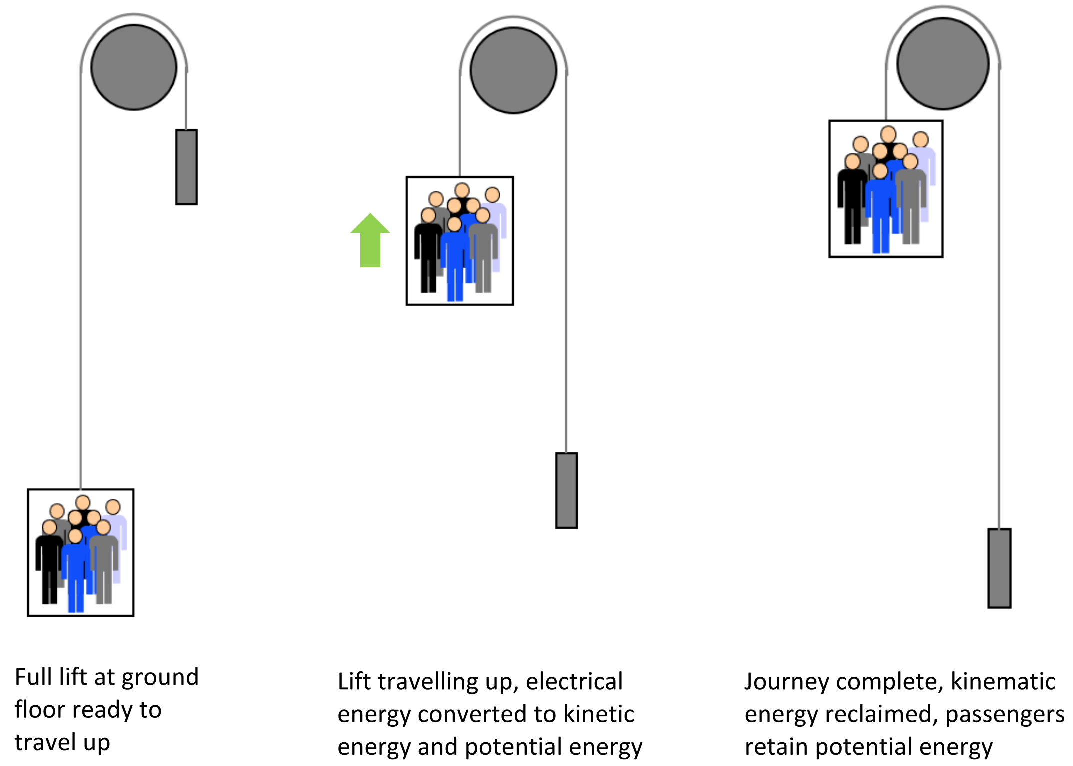

Figure 2 Example ideal lift energy transfer for up journey

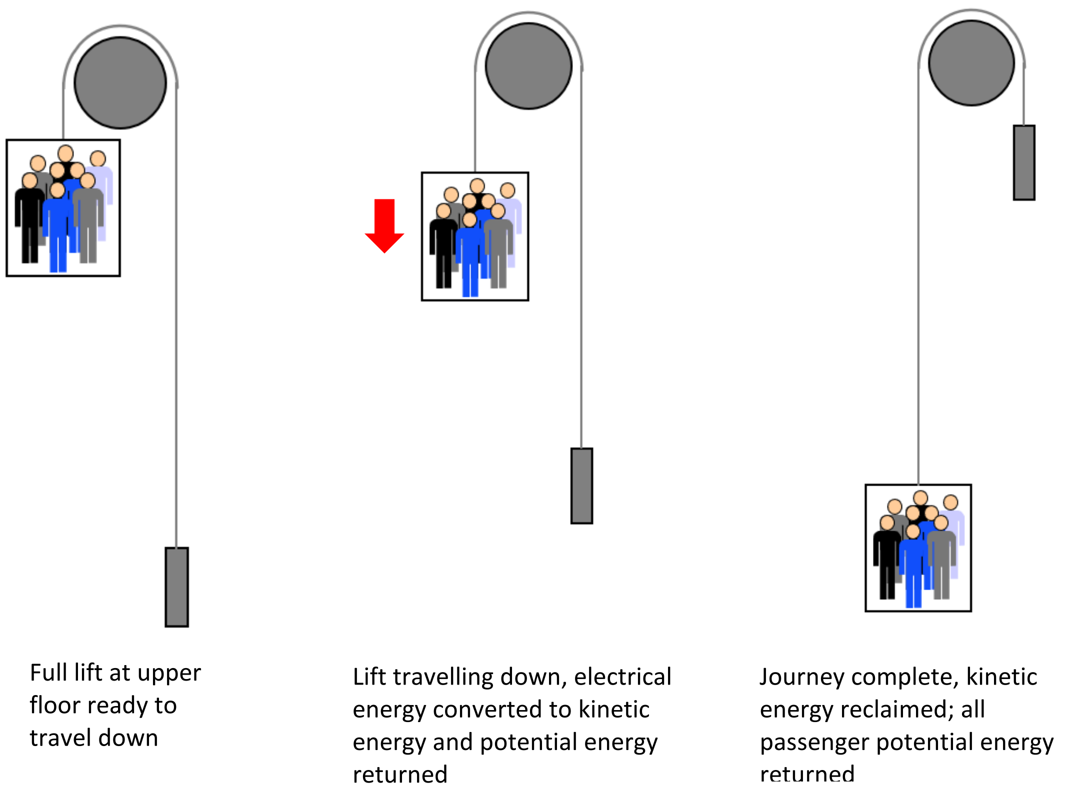

Figure 3 Example ideal lift energy transfer for down journey

3.2 A real scenario

Consider an up journey with a measured speed profile as given in Figure 4.

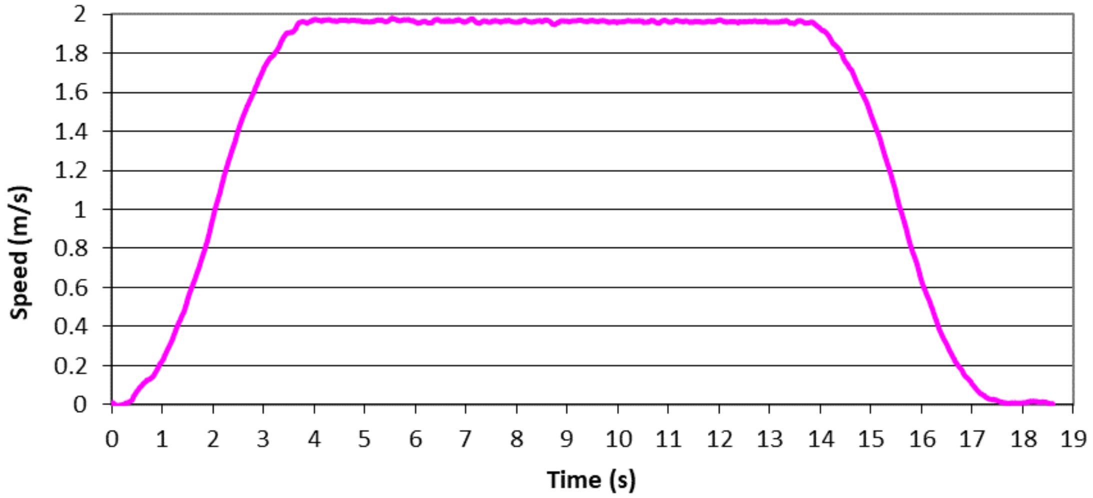

Figure 4 Measured speed profile

The energy consumption of a loaded car travelling up was measured as shown in Figure 5 [6]. Travelling up, the lift reaches full speed after approximately 4 seconds. Once at full speed, it draws a relatively constant 30 kW until it starts to decelerate. The energy consumed is 0.11 kWh. The energy consumed by the same loaded car travelling down was measured as shown in Figure 6. As this is a regenerative drive, during part of the trip energy is being reclaimed, a total of 0.04 kWh. Unlike the ideal scenario represented by Figure 2 and Figure 3, we have losses; to transport these passengers up and then down the building cost us 0.11 kWh – 0.04 kWh = 0.07 kWh.

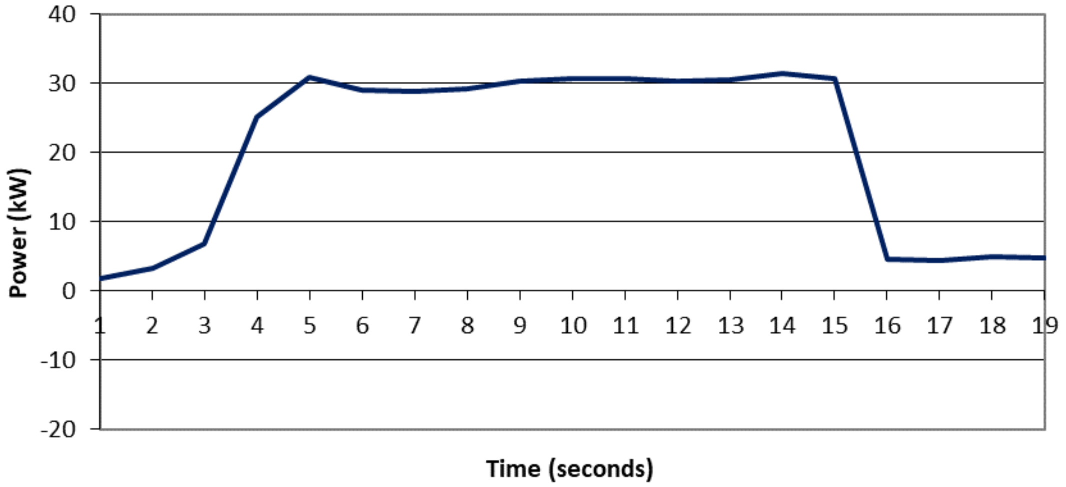

Figure 5 Energy consumption of loaded car travelling up

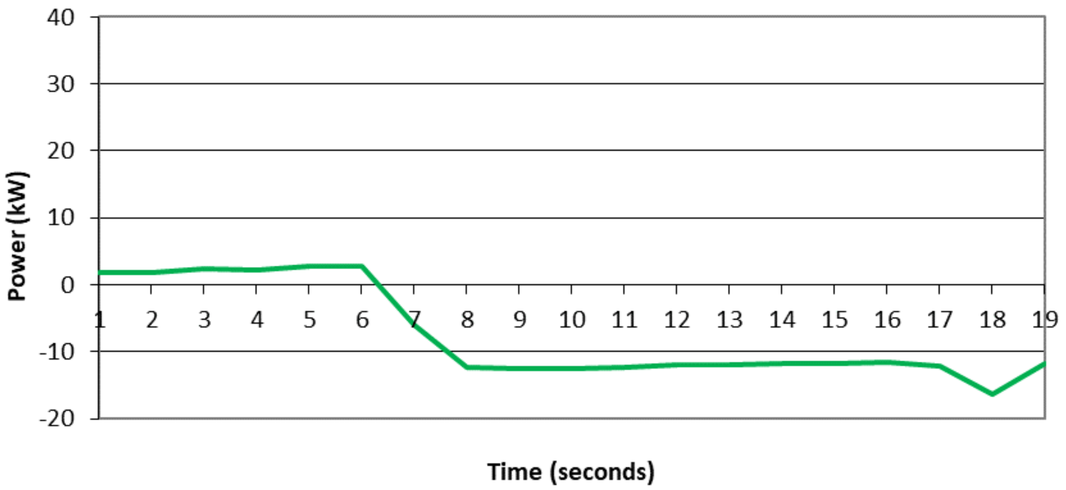

Figure 6 Energy consumption of loaded car travelling down

3.3 Four quadrant operation

A lift is said to operate in four quadrants, as shown in Figure 7. When a lift leaves the ground floor full of passengers, it is motoring, requiring predominantly positive torque (T) in a positive direction. As passengers are dropped off up the building, the counterweight becomes heavier than the lift, so the motor is providing predominantly negative torque in a positive direction. Similarly for a journey down the building, in a negative direction, the motor can be required to deliver both positive and negative torque.

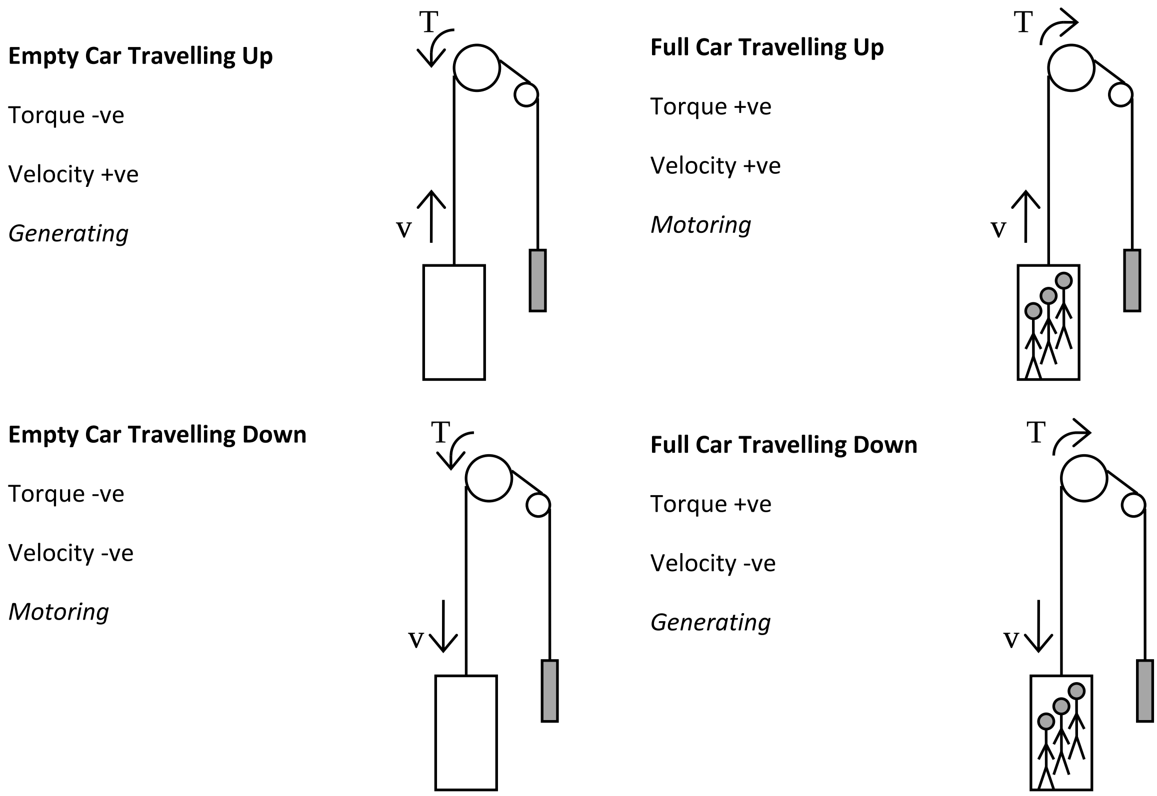

Figure 7 Four quadrant operation of a lift drive

To capture the energy consumption across these four quadrants, Al-Sharif, Peters, and Smith [6] measured the energy consumption across a range of loading in the up and down directions, see Figure

8. Note that when the car is part loaded the mass of the car plus passengers is closer to the mass of the counterweight; in this case, the energy consumption when up to full speed is less, and the peaks (and troughs) at the beginning (and end) of the trip are more marked as the kinetic energy component is more dominant.

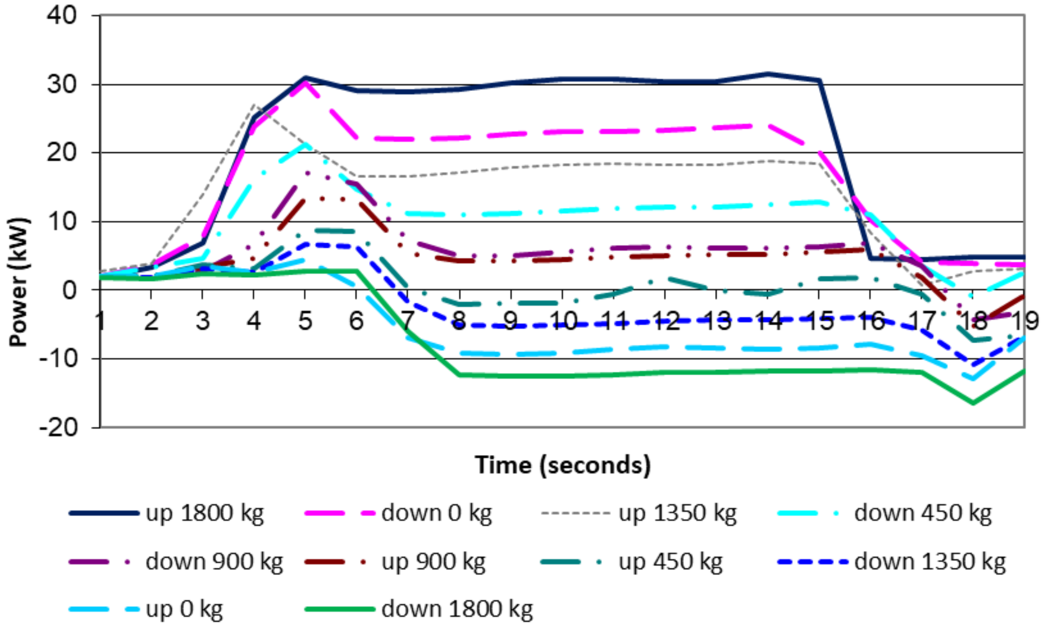

Figure 8 Energy consumption of car travelling up and down for a range of loads

3.4 Non regenerative drives

If the lift drive is not regenerative, then no energy is reclaimed. The best-case equivalent of this is Figure 9. To transport these passengers up and then down the building now cost us 0.11 kWh + 0.00 kWh = 0.11 kWh rather than 0.07 kWh.

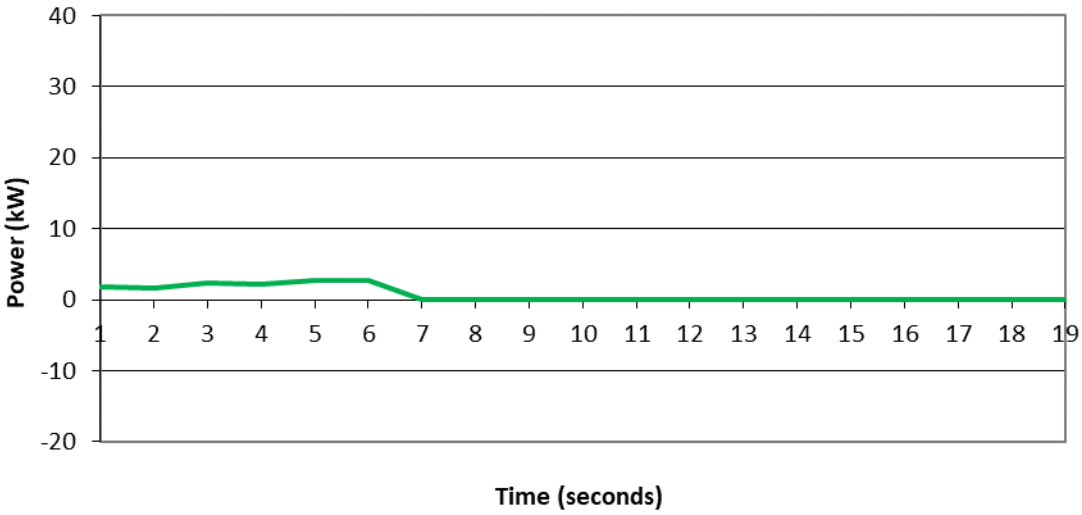

Figure 9 Energy consumption of loaded car travelling down without regeneration

3.5 Energy consumption when idle

Most of the time a lift is idle because there are no calls to serve, or passengers are loading/unloading. The power consumption while idle is crucial. Our measurements have ranged from under 100W to over 2 kW.

3.6 Passenger demand

Two identical lift groups in two identical buildings will consume different amounts of energy. This is because it is the passengers who create the calls which are allocated by the dispatcher to the lift, resulting in individual lift journeys carrying different numbers of people. The number of trips, direction and car loading for the trips is determined by the passenger demand and the dispatcher allocating individual passengers to lifts.

4 ENERGY MODELS

Many attempts have been made to define ways of calculating lift energy consumption. A comprehensive review of these is provided by Lorente in her Doctoral Thesis [3]. She reviews methods listed as:

1. Schroeder
2. Doolard
3. CIBSE Guide D Version 2005 & 2010
4. Al-Sharif-Peters-Smith
5. Barney (a) and (b)
6. Hong Kong Code of Practice
7. Swiss Study
8. Comunidad de Madrid
9. VDI 4707 Part 1
10. VDI 4707 Part 2
11. ISO TC178 WG10 (ISO/FDIS 25 745 -1) – First Draft
12. ISO TC178 WG10 (ISO/FDIS 25 745 -1) – Second Draft
13. E4 Project
14. Lindegger
15. Kone
16. Empirical calculation

Lorente comments that some methodologies make their assessment based on a measurement or calculation process including a single round trip (2, 5a, 6, 8). They are only appropriate for making general recommendations. Other methods (1, 3, 7, 9, 10, 11, 12, 13, 14) aim at rating the performance of the product operating in a certain building; this can be done in a simplified manner or by considering usage patterns or usage category tables.

For example, the Schroeder method (1), proposes an energy calculation based on the formulae:

$$E_d = \frac{R \times ST \times TP}{3600}$$

Where E_d is the daily energy consumed (kWh/day), R is the motor rating (kW) and ST is the number of starts per day.

CIBSE Guide D (2000) compared the Doolard (2), and Schroeder (1) methods, concluding that they were inconsistent by almost a factor of two; the simplifications required to reduce the energy estimate to a simple method yield only rule-of-thumb results when it comes to energy consumption.

The empirical calculations (16) reviewed were based on a survey of lift consumption collected in conjunction with a questionnaire asking a variety of technical and operational questions. An equation was developed which linked the energy use to the lift drive technology and building size. The authors acknowledge that the formulae will not work other than for the buildings surveyed.

Improving on these methods, Barney and Lorente ran thousands of simulations [7] to build formulae and tables which are claimed [8] to be the most accurate public domain energy model. They are probably correct. The work is now applied in ISO 25745-2: 2015 [9].

Nevertheless, the most accurate methods (4, 5b, 15) recognize the importance of traffic and passenger handling strategies, linking their models directly with traffic simulation programs.

The model developed by Al-Sharif, Peters, and Smith [6] is acknowledged by Lorente as the most accurate model available [3]. It models every passenger journey and corresponding lift trip such that the energy consumed can be calculated on a trip-by-trip basis. A mathematical model of the lift energy consumption was developed which could be calibrated to a specific installation, for example, the measurements given in Figure 8, after calibration yield a set of power consumption curves for all four quadrants, as illustrated in Figure 10. The mathematical model then allows for any trip length and car loading, up and down. This trip-based model will provide the most accurate results if calibrated correctly and if the traffic is known. It is patented by the client it was developed for [10] so is not available in the public domain.

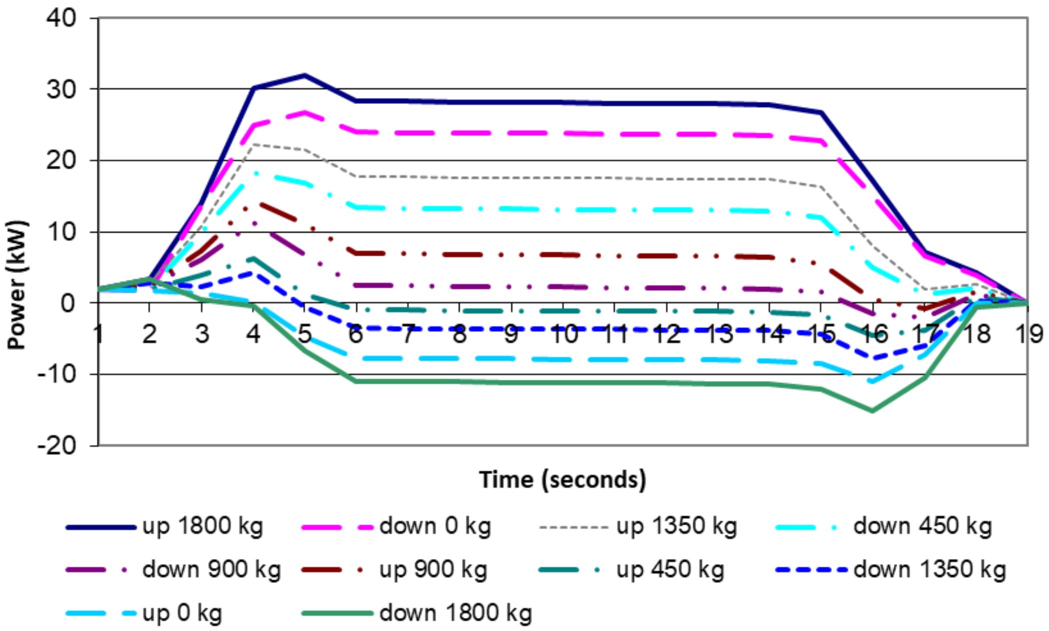

Figure 10 Energy consumption of car travelling up and down for a range of load applying model by Al-Sharif, Peters, and Smith

To offer a simpler model accounting for traffic and passenger handling strategies, one simulation package [11] offers a simple on/off model for the drive at different directions and loads. The equivalent power consumptions curves in Figure 10 become Figure 11.

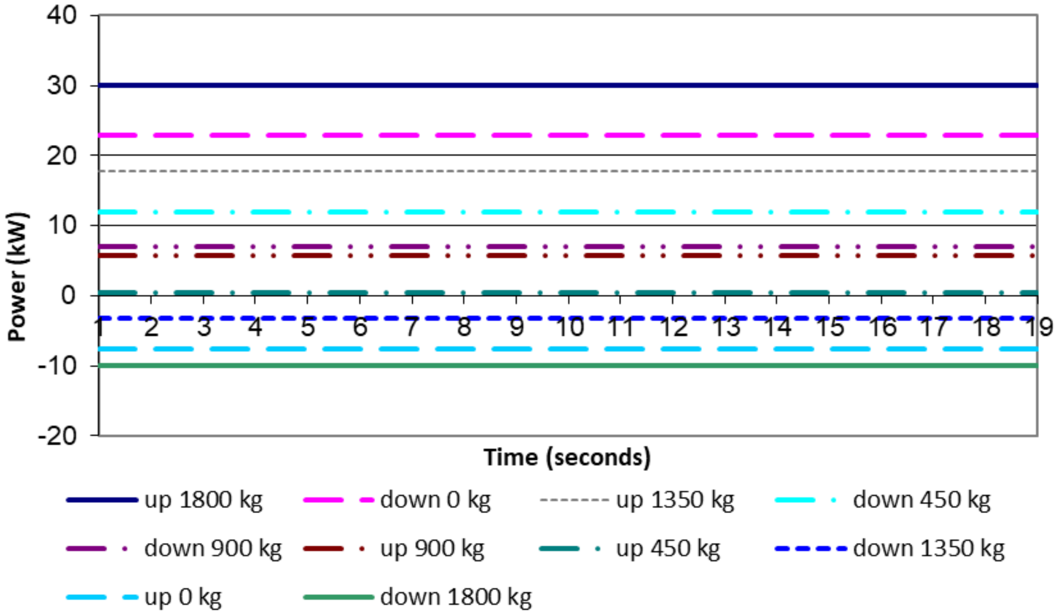

Figure 11 On/off energy consumption model

This approach overestimates the power consumption while the lift is accelerating and decelerating. A better approximation would be, at the beginning of the trip while the lift is accelerating, to draw a straight line from 0 to the power consumption at full speed. And, as the lift is decelerating, another straight line from the power consumption at full speed to 0. The approximation at the beginning of the trip will be an underestimate as we are drawing power to give the system kinetic energy. But that underestimate will be mostly corrected by the overestimate at the end of the trip as the kinetic energy is reclaimed, see Figure 12.

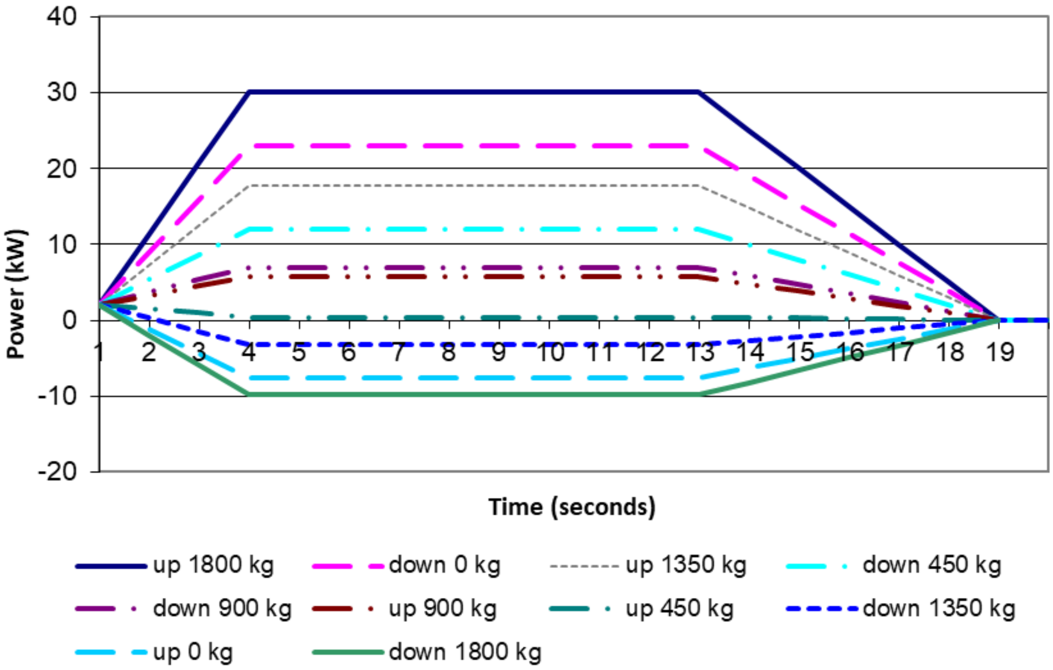

Figure 12 On/off energy consumption model with beginning and end of trip set to 0

This approach provides a trip energy consumption which compares favorably with the more complex model.

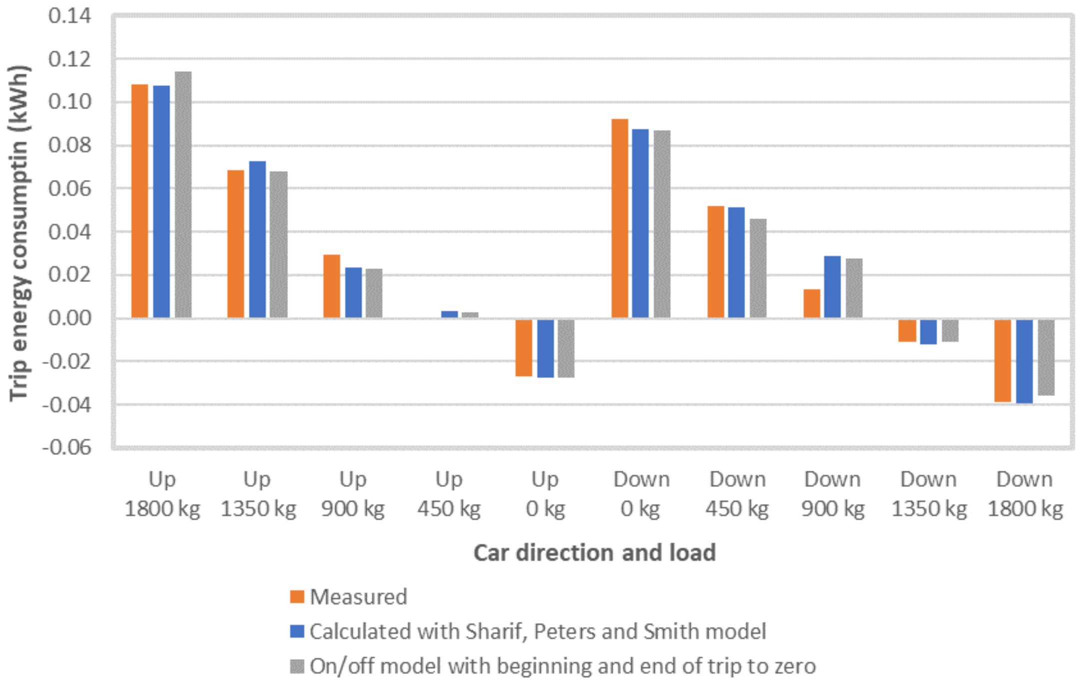

Figure 13 Comparison between measured energy consumption, complex and simplified models

5 CONCLUSIONS

Anyone denying climate change or the importance of reducing our carbon emissions would rightly be considered the modern-day equivalent of a flat-earther. The environmental impact of lifts is not solely due to the energy they consume, but it is a major component. As the climate crisis heightens, buildings get taller and energy prices soar, understanding the energy consumption of lifts becomes increasingly important. If we understand and measure lift energy consumption, we are in a better position to assess improved lift solutions.

Energy modelling of lift systems is complex. There have been excellent attempts to provide formulae and table-based estimates of lift system energy consumption. Without access to a simulation model, the most authoritative of these is presented in ISO 25745-2 [9]. However, without considering all-day passenger demand profiles and the impact of traffic control systems, even the ISO method will only ever offer a rule of thumb estimate of energy consumption.

Applied with simulation, advanced models [6] do offer accurate modelling of individual lift trips. The contribution of this paper is to offer a simpler approach. In the example presented, little accuracy is lost with the proposed simplification. The simpler model proposed in this paper provides a pragmatic, public domain solution which is easier to calibrate and apply in any simulation software.

The final challenge remaining is calibration. For this, the industry needs to collect "big data" on passenger demand and energy consumption and make it available in the public domain. This is technically possible to do and should not need to add major costs if specified early on new projects.

REFERENCES

[1] R. Peters, "Green Lifts?," *Proceedings of CIBSE National Conference,* 1994.

[2] M. Berners-Lee, There Is No Planet B: A Handbook for the Make or Break Years, Cambridge University Press, 2019.

[3] A. M. Lorente Lafuente, Life Cycle Analysis and Energy Modelling of Lifts, Zaragoza: University of Zaragoza, 2013.

[4] A. M. Lorente Lafuente and J. L. Núñez Bruis, "Environmental Impact of Lifts," *Proceedings of the 4th Symposium on Lift and Escalator Technologies,* 2014.

[5] M. Goedkoop and R. Spriensma, "The Eco-Indicator 99: A Damage Oriented Method for Life Cycle Impact Assessment," PRé Consultants B.V, Amersfoorttel , 2001.

[6] L. Al-Sharif, R. Peters and R. Smith, "Elevator Energy Simulation Model," *Elevator Technology 14,* 2004.

[7] A. Lorente, J. Núñez and G. Barney, "Energy Models for Lifts - Determination of Average Car Load, Average Travel Distance and Standby/Running Time Ratios," *Proceedings of the 2nd Symposium on Lift and Escalator Technologies,* 2012.

[8] G. Barney and A. M. Lorente, "Simplified Energy Calculations for Lifts Based on ISO/DIS 25745-2," *3rd Symposium on Lift and Escalator Technologies,* 2013.

[9] International Organization for Standardization, "ISO 25745-2 Energy performance of lifts, escalators and moving walks - Part 2: Energy calculation and classification for lifts (elevators)," ISO, Geneva, 2015.

[10] R. Smith, R. Peters and L. Al-Sharif, "Method and apparatus to prevent or minimize the entrapment of passengers in elevators during a power failure," United States Patent assigned to TK Elevator Corp, 2009.

[11] Peters Research Ltd, "Elevate Traffic Analysis and Simulation Software," [Online]. Available: http://www.peters-research.com.

BIOGRAPHICAL DETAILS

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 principal author of Elevate, elevator traffic analysis and simulation software.

Dynamic Simulations for Lift Health Diagnosis

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Keywords: system simulations, lifts, diagnosis.

Abstract. System simulations introduce new opportunities in lift health diagnosis, due to their quasi-real time computation and cross disciplines coverage.

The approach is based on an object-oriented model, where controller, machinery, hoisting and building layout are interconnected for computing the lift dynamics for its entire ride.

While most of the components impacting the dynamics of lifts are described by blocks with certain physical parameters, others are described more in detail, including local flexibility and eigenfrequencies expression. The created model is structured, modularized, and parametrized.

Several simulation outputs can be used for diagnosis: car position, velocity and vibrations, guide shoes forces, machinery current and torque, however in this paper the focus is on using spectrums of car vibrations for this purpose.

Healthy and several malfunction behaviors are computed and validated using system simulation, proving that this approach can be used for identifying the faults and providing solutions for mitigating them.

1 INTRODUCTION

KONE has a long history, where mechanic, electro-magnetic, thermal, acoustic and many other simulations have been used for virtual prototyping. The target being the optimization of component design, performance, or fulfilling the code requirements.

System simulations came later in KONE, as well as in other industries, because they require cross-discipline computation, cross-functional cooperation, and extensive validation.

However, the front-loaded effort is worth it. Due to real time or quasi-real time computations, the applications of the simulations can be extended beyond the development phase of the components, towards the entire lifetime of the equipment. System simulation can provide a better understanding of the lift or escalator reliability, lifetime performance, health monitoring, diagnosis, remote maintenance, and software testing.

The benefits of integrating synthetic data – the results of simulations - with measured data, collected from the systems, for a better diagnosis of the health of equipment, using machine learning algorithms, are discussed in several articles [1, 2].

The focus of this paper is to answer the research question: can simulation provide consistent, robust synthetic data that can be used for training machine learning algorithms in diagnosing lift health?

Studies for answering this question have been discussed in several master theses conducted in KONE [3, 4, 5, 6]. The conclusion is that by using adequate computational strategy, modularized and parametrized simulation models, a big step can be made toward better lift monitoring and health diagnosis.

2 SELECTION OF THE COMPUTATIONAL STRATEGY

The main requirements of using simulations during the operational phase of the equipment are the real or quasi-real computational time and the model possibility for parametrization. The challenge of using a fast computation method is the ability to capture the simulated physical phenomena, with acceptable accuracy.

High fidelity methods, such as finite element, are not effective for computing a fleet of complex equipment with large variations in dimensional and running parameters. Especially if results for computing the performance of new equipment are needed fast in the development phase.

A fast computational method, for example, an object-oriented method, can provide real time results; however, not all the phenomena, for example, local eigenfrequencies, can be described. For this reason, several methods have been combined. Ranking of several methods based on their computational time and fidelity of the results is presented in Figure 1.

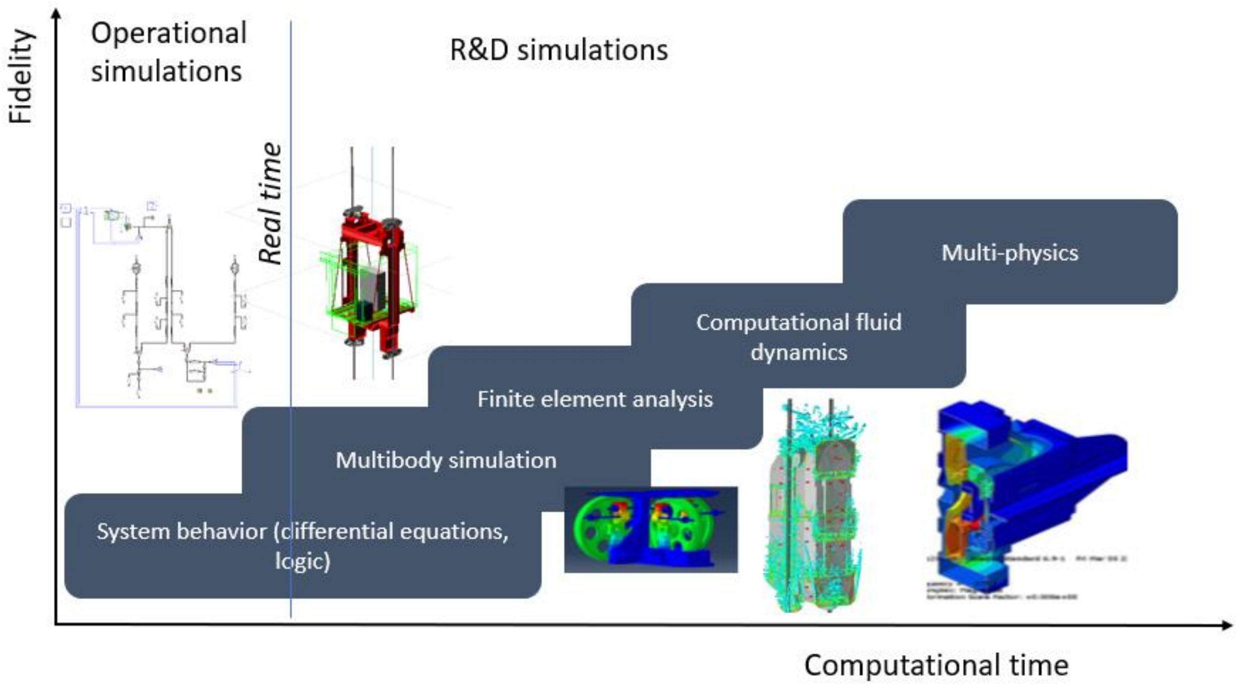

Figure 1 Ranking of different computational methods

Another challenge was the identification and selection of the components contributing to the lift dynamics and the method to describe their behaviour.

For creating the lift model, SimulationX software [7] has been selected. The software is based on the object-oriented description language Modelica [8]. The model contains blocks representing critical components with impact on lift dynamics. Each block is defined individually with mechanical, electrical, or logical inputs. These blocks represent machinery including its mechanical, electrical inputs, the motion control algorithm; the hoisting, including ropes and pulleys; car-sling-doors subsystem including their guide shoes and guide rails; lift safety features: safety gears, buffers, sensors; and building layout details, for example distances between floors, pit depth, and others (Fig. 2). The blocks are linked through specific connections.

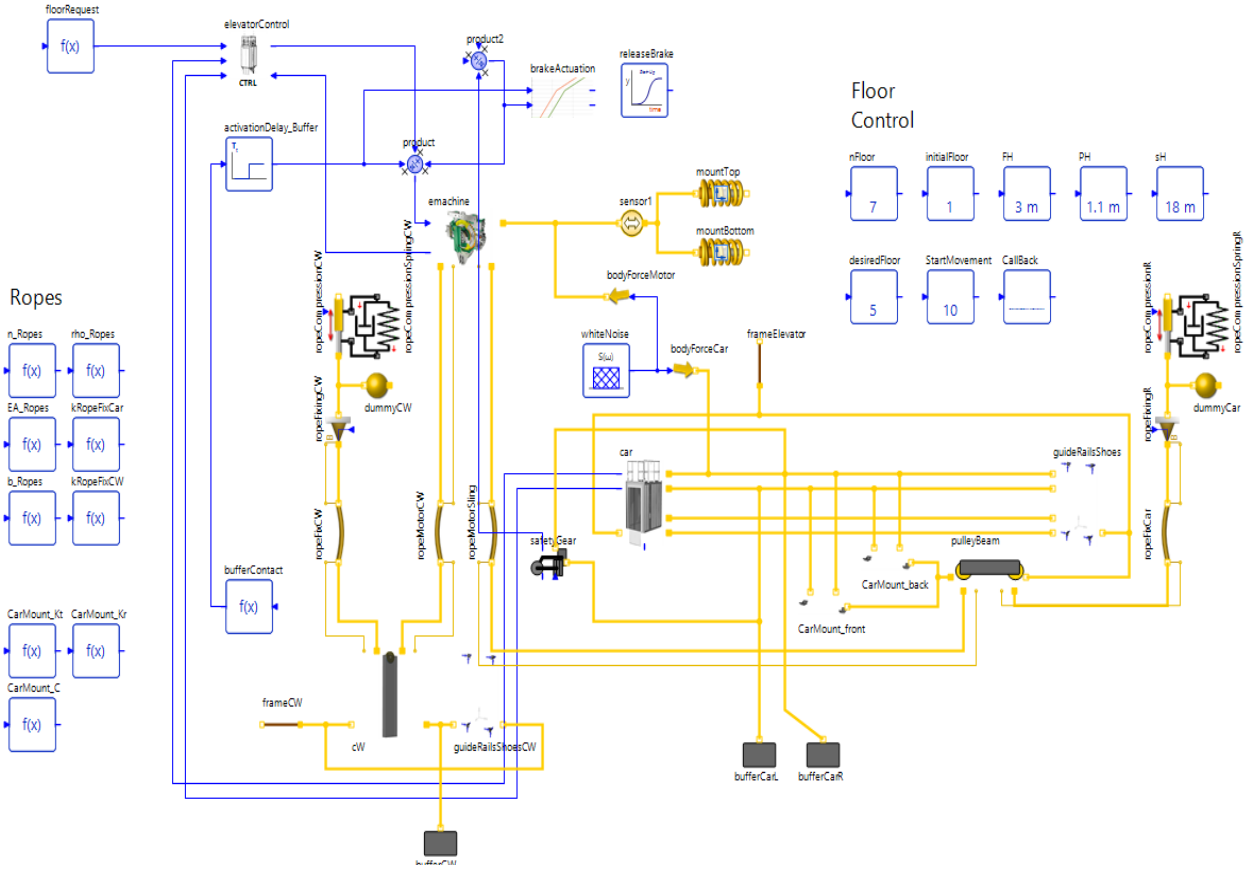

Figure 2 The architecture of lift model

The outputs of the simulation depend on the application, for further integration with measured data, the selected output of this model had to be easily collected from sites. For this reason, the three-dimensional car vibrations, velocity, and position in the shaft have been selected.

3 INPUTS

Each block in the model is described by inputs collected from different sources: product documentation, laboratory results, geometrical models, results of other simulation methods, or software code.

3.1 Mechanical inputs

The behaviour of each block is described with differential algebraic equations, constant or variable in time during simulation. However, the inputs describe the entire block – as an entity, therefore if the structure contains high space variations in the behaviour, for example, one component is very stiff while another is very flexible, the structure is divided into multiple blocks with similar behaviour.

In the machinery case, the structure has been divided into three blocks with similar properties: the frame, including the traction sheave, the top mount, and the bottom mount (Fig.3).

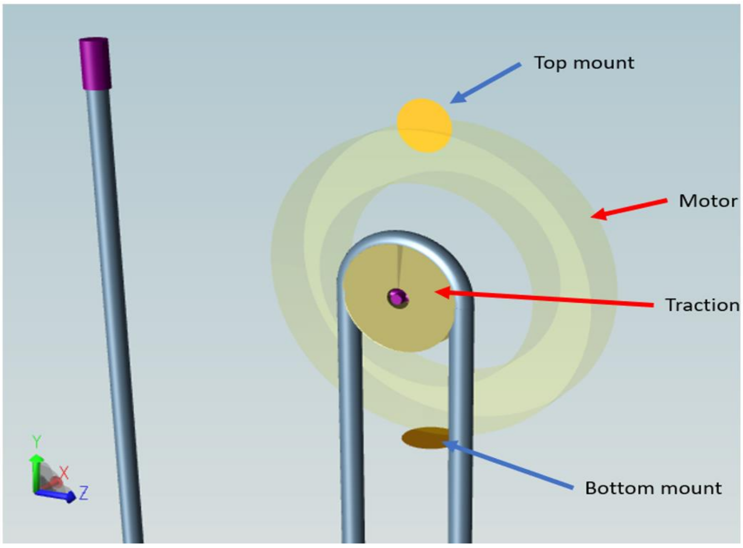

Figure 3 The machinery blocks

For each block, mass, centre of gravity and inertia tensor around centre of gravity are selected from documentation or 3D geometrical models.

The stiffness tensor of the blocks can be estimated as rigid, measured in the laboratory, or computed using an analytical or numerical method, for example, finite element method (Fig.4) calculated in this paper with the software Ansys [9]. The damping tensor can be estimated based on the stiffness tensor or measured in the laboratory, if possible.

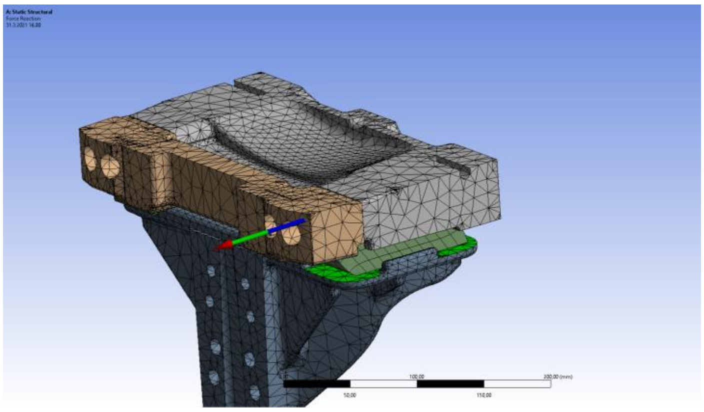

Figure 4 The bottom mount stiffness calculation

The computational time requirements create limitations in the number of blocks that can be created in the model. In addition, for certain components, the local eigenfrequencies, which are the frequencies at which the component tends to vibrate in absence of any driving force [10], may have a significant contribution to the in-car vibrations.

In this case, two different computational methods have been selected: finite element and meshless method [4]. The selection of the computational method depends on the complexity of the structure. For machinery bedplate, the recommended method for eigenfrequency extraction is finite element, for which Ansys software [9] has been used.

For sling-car-door subsystem, due to its complexity, the recommended method is the meshless one, computed in this paper with the software Simsolid [11]. The main difference between these methods is that for FEM, the structure must be divided into smaller substructures called elements, whereas meshless solutions remove the need for structure discretization and instead describe the structure only by the set of nodes used for approximation functions (Fig. 5). Therefore, instead of having strict pre-defined element-based shape functions, the meshless method has shape functions based on nodes in a local support domain. Otherwise, the same variational approach is used for both methods.

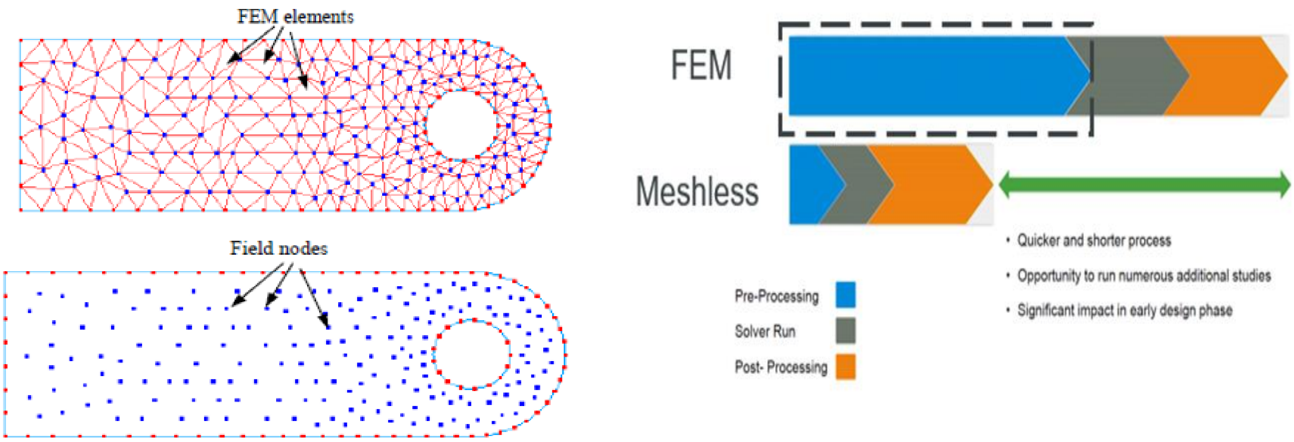

Figure 5 Comparison between finite element and meshless method

The meshless method is faster because it does not require geometry simplification, however, the FEM is more accurate, if the geometry simplification is minimum, which is rarely the case.

Figure 6 Eigenfrequency extraction for sling-car-doors subsystem with meshless method

Regardless of the chosen solution, a frequency response analysis is required in order to rank the vibrational modes, and include in the lift model just the significant ones in the frequency region of interest, between 0 and 100Hz (Fig.7).

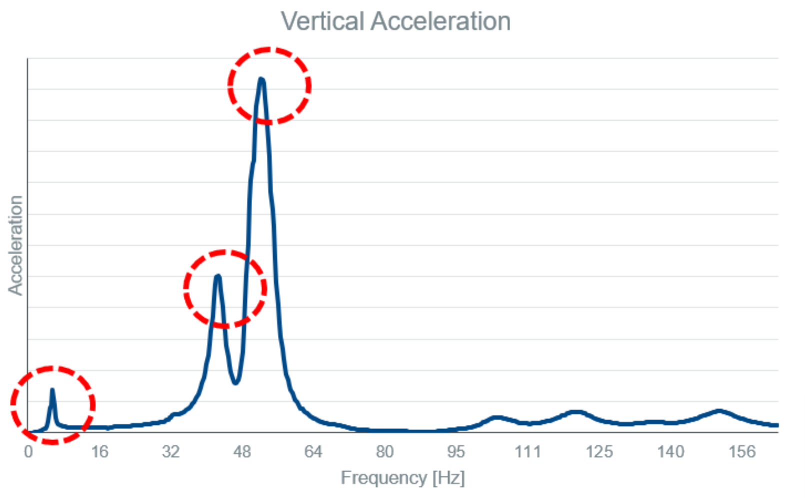

Figure 7 Frequency response of the sling-car-door susbsystem

3.2 Electrical inputs

The model of machinery has been done as an equivalent circuit with an ideal invertor (Fig.8), however, the model can be mode detailed based on the simulation targets.

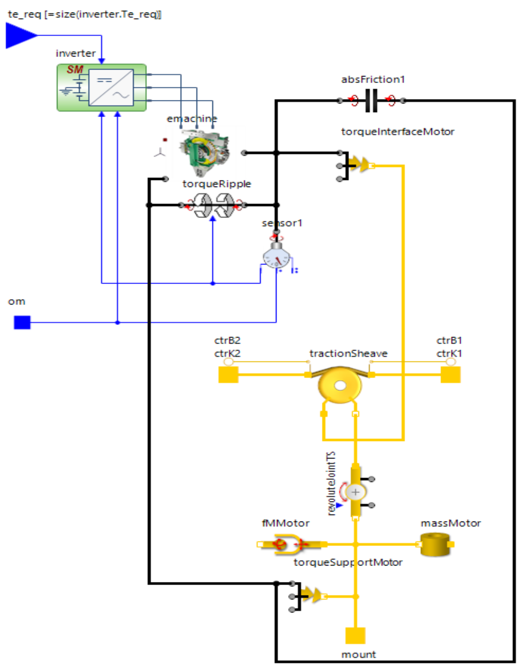

Figure 8 Machinery blocks including mechanical and electrical inputs

3.3 Controller structure

A motion controller, that calculates the desired car velocity has been modelled, using the real lift velocity profile algorithms packed in a mock-up function (Fig.9).

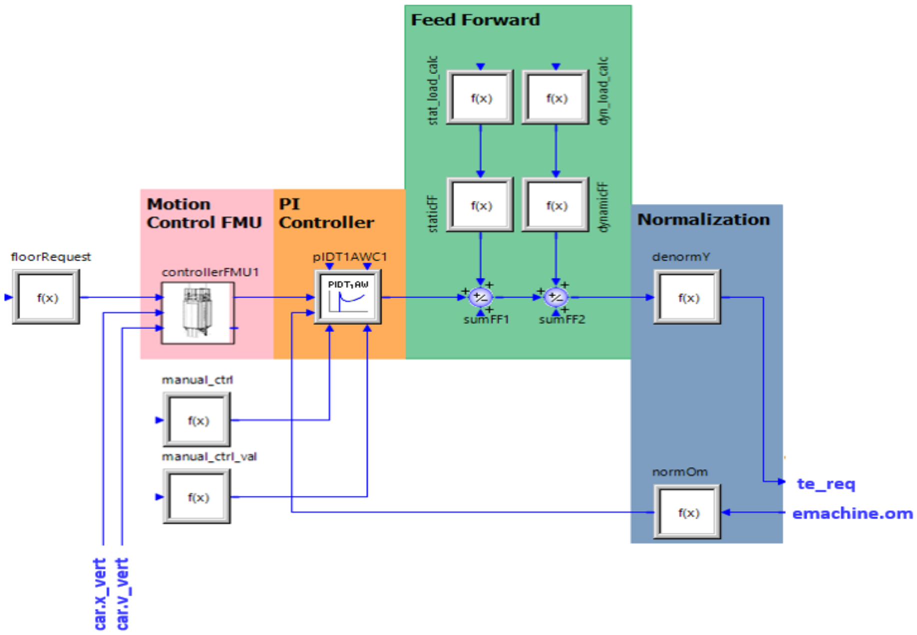

Figure 9 Motion controller

4 THE RESULTS OF THE SIMULATION

Several types of analysis can be done using the model described before: normal or faulty runs, car sag and bouncing, safety tests, etc. In this paper, the focus is on normal and faulty runs and the possibility of identifying the root cause of certain faults in the measured data.

The procedure for identifying the root cause of the malfunction was the utilization of the spectrum for in-car vibrations in three directions, for the time period when the car was running at a constant speed, between different floors.

By comparing the computed spectrum of an "ideal" lift with the median measured spectrum of a "real lift" (Fig.10) collected during 274 rides, we can conclude that in the real lift, there are more excited frequencies in the car. The sources of these excitations can be identified from known rotational frequencies or eigenfrequencies of the system. Each of these sources can be simulated separately or simultaneously in the system model (Fig. 11).

In the same manner, unknown variables in the system, such as guide rail misalignments and damping, can be calibrated in the simulation based on measured data. After model calibration, monitoring of the lift health can be performed with good confidence, relying on the fact that analysing a big volume of data will increase the accuracy of the diagnosis.

Machinery eccentricity due to manufacturing tolerances, machinery harmonics of supply frequency, harmonics of flat spots of rolling guide shoes and harmonics of the contact between ropes and pulleys due to the manufacturing or condition of the wires and strands of the ropes and other faults can be simulated.

These faults can be labelled and identified in the measured vibrations of the cars, by using trained machine learning algorithms. In addition, by knowing the frequency response of the car, based on the system simulation of the lift, these amplitudes can be monitored and a threshold can be used to flag potential changes and malfunctions before they become critical.

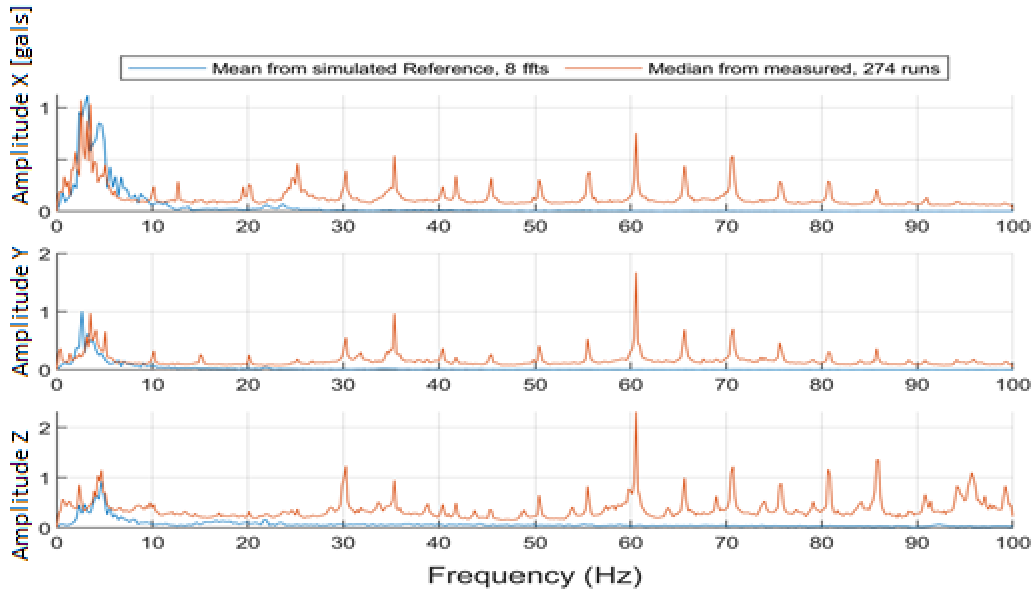

Figure 10 Spectrum of in-car vibrations for the constant speed period Comparison between ideal lift and measured lift

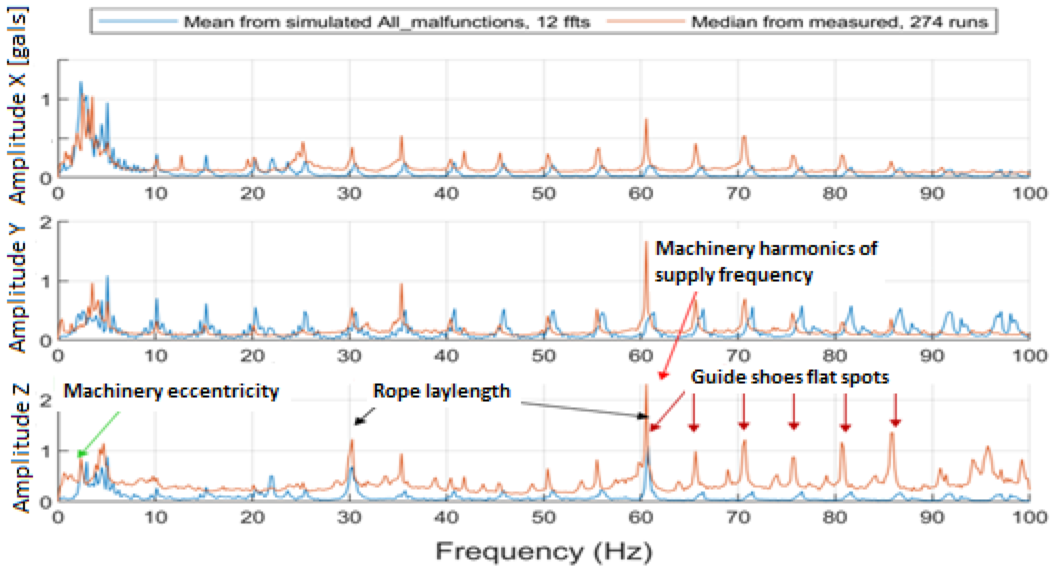

Figure 11 Spectrum of in-car vibrations for the constant speed period Comparison between lift with certain malfunctions and measured lift

5 DISCUSSION

In this paper, a combination of object-oriented simulations with finite element and meshless method is presented for the normal run of an ideal lift and a lift with certain malfunctions.

After post-processing of the simulated and measured in-car vibrations, one can conclude that this procedure can be used for monitoring and identifying malfunctions of the lift using trained machine learning algorithms with synthetic data.

REFERENCES

[1] P. Klein and R. Bergmann, “Data Generation with a Physical Model to Support Machine Learning Research for Predictive Maintenance”, *Business Information System II, University of Trier Germany*, ISSN 2191-5652, Springer series, 2018.

[2] Y-C. Zhu, D. Wagg, E. Cross, and R. Barthorpe, “Real-time digital twin updating strategy based on structural health monitoring systems”, *Conference proceedings of Society for experimental mechanics*, 2020.

[3] M. K. Gupta, “Simulation of vertical people transportation system”, *Master thesis, Lappeenranta- Lahti University of Technology LUT, Finland*, 2021.

[4] J. Leppänen, “Dynamic analysis of elevator in-car vibrations and ride quality using meshless method”, *Master thesis, Lappeenranta- Lahti University of Technology LUT, Finland*, 2022.

[5] D. Gupta, “System simulation of an elevator”, *Master thesis, Tallinn University of Technology, Tallinn, Estonia*, 2021.

[6] M. Lin, “Physics-based simulations of elevator door systems”, *Master thesis, Aalto University*, Finland, 2021.

[7] SimulationX [https://www.esi-group.com/products/system-simulation], 2022.

[8] SimulationX [https://en.wikipedia.org/wiki/SimulationX], 2022.

[9] Ansys [https://www.ansys.com/], 2022

[10] P. Laszlo and G. Tarjan, *Mechanics of Civil Engineering Structures*, Woodhead Publishing, ISBN 978-0-12-820321-7, 2021

[11] Simsolid, [https://www.altair.com/simsolid], 2022

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Energy Efficient Buildings
Assessing The Impact of Lifts

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Keywords: lift, energy, carbon, embodied, operational.

Abstract. As the impact of climate change becomes ever more visible, society appears at last to be reacting and making changes aimed at mitigating its impact and protecting our established ways of life. Most if not all human activity affects our planet, and the creation, operation, modernization, and replacement of buildings is no exception.

The lift industry therefore has an important part to play in minimizing its impact on our climate; the creation of new lift equipment consumes energy which is quantified by its embodied carbon credentials, whilst the use of lifts consumes energy characterised by its operational carbon credentials. These carbon credentials play a key part in the assessment of a building's energy performance and as an industry we now need to recognize this and refine both the processes and the accuracy with which we model the impact.

This paper explores some of the current guidance and assessment methodologies touching on such established documents as the British Standard BS EN ISO 25745 [1]. Application of these methodologies will be reviewed against a real-world case study, and conclusions and recommendations presented on how the industry might refine future assessments towards more realistic results.

1 BACKGROUND

Whilst the debate on the causes of changes to our climate may continue for some time, the fact that our climate is changing appears to be undeniable. This year's news seems frequently to feature stories from around the world reporting on the negative impacts of changing climate; from severe wildfires in California and the Mediterranean, to catastrophic flooding in Australia, to the driest July in the United Kingdom since 1935 [2].

Over recent years society and our governance has started to act introducing rules and regulations aimed at mitigating the impact of climate change. The UK introduced the Climate Change Act [3] in 2008 setting a legally binding target for 2050 to reduce greenhouse gas emissions by at least 80% compared to 1990 levels. Good progress is being claimed with a 38% reduction in UK emissions between 1990 and 2019 [4], however measured against the growing evidence and concern this was seen to be insufficient and in June 2019 the UK government went further with an amendment to the Climate Change Act setting a legally binding target to achieve net zero greenhouse gas emissions from across the UK economy by 2050. The scale of the challenge is clear to see, and the impact of failure for future generations unthinkable.

This paper however is not intended to spread doom and gloom, nor to expound on the issue of climate change. The scale of the challenge is daunting, and it is often hard to see the wood for the trees and to see what part, however small, we can play. This paper's intent is to provide some comment, guidance and opinion on where the lift and industry "fits" within the challenge and how best might our industry respond and play our part in driving down damaging emissions.

Back in 2015 the United Nations (UN) published their 17 Goals Sustainable Development Goals (SDG) [5], as shown in Figure 1 below.

Figure 1: United Nations 17 Sustainable Development Goals (SDG)

These goals, shared by all United Nations member States, are intended to provide a blueprint for peace and prosperity for people and the planet, now and into the future. They were and remain an ever more urgent call for action by all countries, and in the UK one of the major catalysts for the development of methodologies to achieve the government's net zero 2050 emissions target.

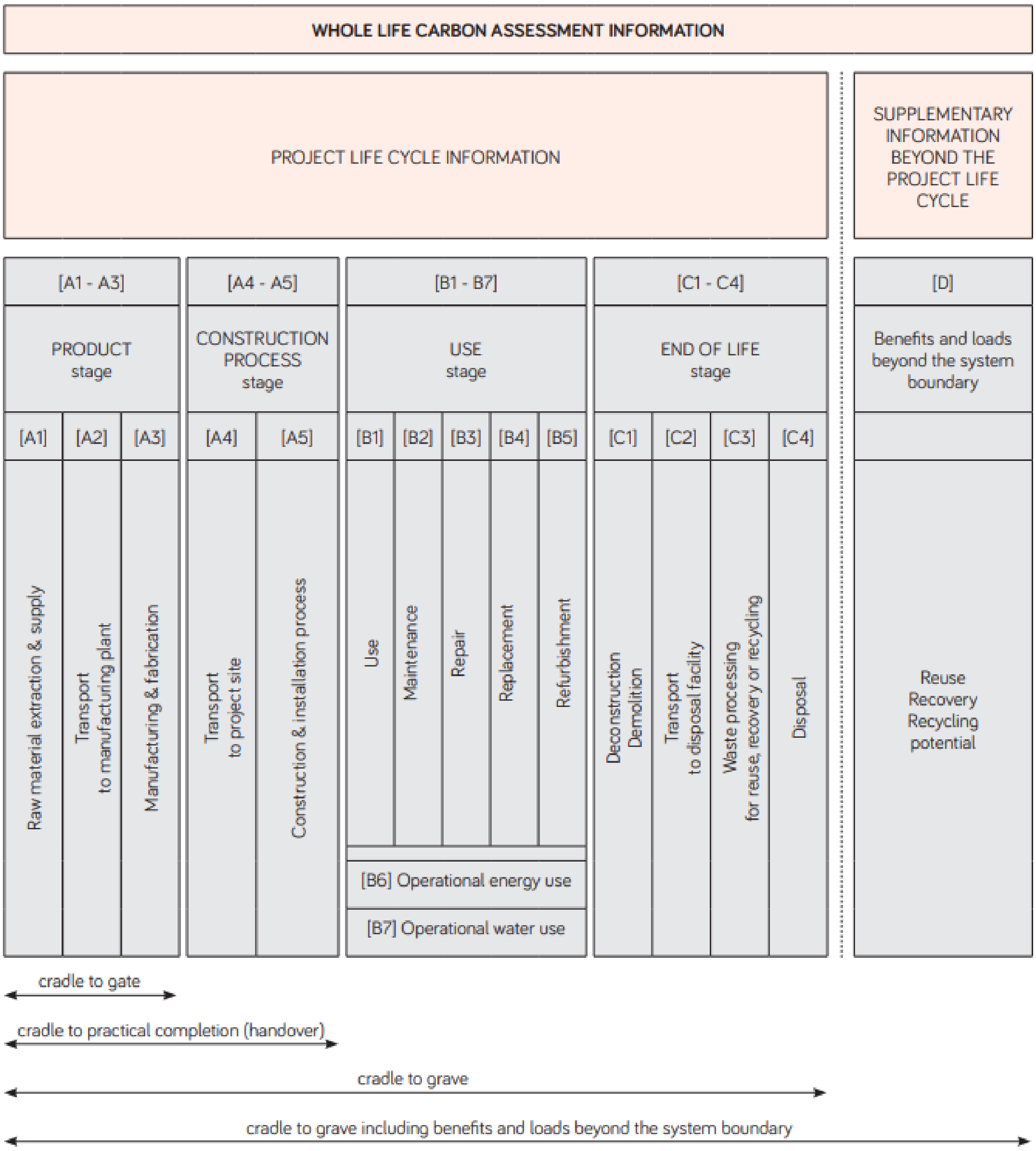
Buildings are complex with many interrelated elements such as structure, façade, mechanical systems, electrical systems, clean and wastewater systems, fire protection systems, and of course lift systems. The manufacture, shipping, installation, operation, removal and modernization of each of these systems produce damaging carbon dioxide (CO_2) emissions. Reducing the volume of CO_2 (typically referred to in this context as simply carbon) emitted during the lifetime of a system is the ultimate goal.

The carbon created over a system's lifetime is referred to as Whole Life Carbon (WLC) and in itself is a complex concept. It can typically be thought of as comprising two fundamental components:

- Embodied Carbon – the total CO_2 emitted in producing materials, estimated from the energy used to extract and transport materials as well as from the manufacturing process itself.
- Operational Carbon – the total CO_2 emitted due to the building's energy consumption in use.

2 ASSESSMENT METHODOLOGIES

In the UK many respected bodies have responded to the government's net zero legislation with guidance and methodologies for the assessment of carbon emissions. Key amongst these is the Royal Institution of Chartered Surveyors (RICS) methodology for undertaking detailed carbon assessments for buildings (RICS Whole life carbon assessment for the built environment professional statement 2017) [6]. Figure 2 below illustrates the modular structure of the RICS PS, which also aligns with the recommendations set out within BS EN 15978.



Modular reporting structure of BS EN 15978 as used in RICS PS
Module A: Product and Construction stages; Module B: In use; Module C: End of Life; Module D: potential benefits through reuse or recycling.

Figure 2 – RICS PS Whole Life Carbon Assessment Information

This approach covers both operational carbon in terms of energy use and water use (modules B6-B7), and embodied carbon emissions (modules A1-A5, B1-B5, C1-C4 and D). It is of note that module D provides opportunity for “credit” related to reuse or recycling of materials at end of life, supporting the circularity concept of maximizing the sustainability value of created materials.

For buildings WLC is typically reported in units of $kgCO_2e/m^2$ Net Internal Area (NIA), where CO_2e is carbon dioxide equivalent, which is a measure of all produced greenhouse gases associated with the system being presented in terms of the amount of pure CO_2 that would create the same amount of warming.

The carbon cost of materials is commonly assessed using Environmental Product Declarations (EPDs) which provide a range of data including embodied and operational carbon. The EPD process is strictly regulated and requires third party ratification. Assessments typically have a validity period beyond which a re-assessment must take place.

3 CASE STUDY

Given the diverse range of materials in a lift, and the global nature of the lift industry's manufacturing plants and installed product base, the challenge of accurately predicting and/or comparing the carbon cost of lifts may at first seem somewhat daunting. However, when viewed through the lens of "don't let perfect be the enemy of good" and an acceptance that it can never be 100% accurate, a set of necessary assumptions unlock the process and allow some 'compare and contrast' analyses to be completed.

Over the past few years, the lift industry has taken good strides in advancing the level of information published as EPDs. ISO 14026 and EN 15804 are typically used as standards to define core product category rules (PCR) for construction products such as lifts. The PCR defines a consistent approach for assessment and describes which stages of a product's life cycle should be in the EPD; this consistent approach is intended to provide the ability for different products to be compared in terms of WLC, with the ultimate goal that products with a lower carbon footprint are selected in preference to those with a higher impact..

However, this 'compare and contrast' process needs care in application; the data is detailed and complex and needs to be reviewed and interpreted by skilled practitioners. It is important to ensure the products being compared are truly equivalent. For example, it would not be appropriate to compare a 1000 kg, 1.0 m/s, 15 m travel, machine roomless lift with a 1600 kg, 4.0 m/s, 80 m travel, machine above lift; the speed difference will require different drives and machines, the travel difference will create longer guide rails, ropes and travelling cables, and the number of stops will create the need for more landing entrances. It is even important to review the assumptions made in terms of the electricity supply mix applied to the operation and manufacturing modules, and for this some understanding of the geographical location of manufacture and installation is required.

To provide some form of normalization a key PCR defines the concept of the Functional Unit (FU), a measure of the transportation of a load over a distance expressed in tonne (t) over a kilometre travelled (km), where:

$$FU = \%Q \times S_{RSL}$$

Where:

%Q is the average load (t) determined by selecting the appropriate usage category according to ISO 25745-2 Table 1 and multiplying the rated load Q by the applicable average load percentage as per ISO 25745-2 Table 3.

And:

S_{RSL} is the distance travelled over the lifetime of the equipment determined by the average travel distance (ISO 25745-2 Table 2) x number of trips per day (n_d) (ISO 25745-2 Table 1) x number of operating days per year x service life of the equipment in years.

For example, consider a 1600 kg lift serving 9 floors over a travel of 40 m. The equipment has a predicted service life of 20 years, 365 days per year operation, and operates under a usage category 4:

$$FU = \%Q \times S_{RSL}$$

$$FU = (0.035 \times (1600/1000)) \times ((0.44 \times (40/1000)) \times 750 \times 365 \times 20)$$

$$FU = 0.056 \times 96{,}360$$

$$FU = 5{,}396 \text{ tkm}$$

To illustrate the challenges of comparing and contrasting products from different manufacturers the author conducted an informal review of published EPDs for similar mid-range machine roomless lifts from three major suppliers. Extracted in the table below are key data from the EPDs for the manufacturing processes (A1 + A2 + A3) and the operational energy in use (B6). The environmental impact is represented by the Global Warming Potential (GWP).

Table 1 EPD - Comparison Electric Traction Machine Roomless Lift

Supplier	Representative Unit	Declared Functional Unit [tkm]	Upstream & Core Environmental Impact GWP [$kgCO_{2eq}$/tkm]	Energy Consumption In Use GWP [$kgCO_{2eq}$/tkm]	Total Considered GWP [$kgCO_{2eq}$]
1	1000 kg 1.6 m/s 12 stops 35 m travel Usage Class 4 Service Life 20 years	1690	21.706E+00	7.89E+00	13,356
2	1000 kg 1.6 m/s 8 stops 21 m travel Usage Class 4 Service Life 20 years	3035	3.8767E+00	8.62E+00	37,928
3	630 kg 1.0 m/s 5 stops 12 m travel Usage Class 3 Service Life 25 years	761	11.232E+00	5.11E+00	12,437

So which supplier has the most environmentally friendly product? Well, it's hard if not impossible to say, at least from the data analyzed in this exercise. Whilst key characteristics such as rated load, speed, usage class and service life are the same for supplier #1 and #2, the travel and stops are different. Supplier #3's published data did not seem to include a 1000 kg lift of any configuration, so a smaller and slower 630 kg lift was selected, with a lower travel, different usage class, and longer service lifts. The EPD process requires a representative equipment configuration applied to a theoretical lifetime duty cycle. Unless the equipment and lifetime duty cycle, i.e. the Functional Unit (FU), is the same or similar, valid comparisons are hard to draw.

Perhaps a more transparent comparison, for the energy in use module at least, can be provided by the ISO 25745-2 methodology for the calculation and classification of energy performance for lifts. This standard defines the methodology for the classification of energy performance for a lift. It is somewhat simplified by necessity, and it is of note that the method is intended to only be applied to single lifts and therefore any energy efficiencies realized in dispatching logic across a group of lifts is not recognized. Regenerative drive systems are also not clearly recognized by the method albeit some reference is made to a slightly different method for calculating energy for a lift that draws some or all of its energy from an energy storage system. It is also interesting to note the standard draws the reader’s attention to the fact that there might be a deviation between calculated values and measured on site values in use, and that if this deviation is greater than 20% (a seemingly large factor), an investigation should be carried out.

The methodology set out in ISO 25745-2 is detailed and needs care in application but is logical and robust. It considers the following key elements, and the reader should consult the standard for the detail behind each one:

- Usage category and number of starts per day
- Average travel distance
- Average running energy per metre travel
- Running energy of an average cycle with an empty car
- Load factor and average car load
- Non-running (idle/standby) energy consumption
- Ratio of idle, 5 min standby, and 30 min standby modes
- Running time per day

Application of the above derives the calculated total energy consumption per day, which can then be converted to estimated annual energy consumption. Care should be taken in considering the number of days the lift will operate, for example in an office building it may be appropriate to consider the weekend as a period of predominantly standby mode energy consumption.

The application of the ISO 25745-2 methodology typically results in a table of results for a lift system which is then compared against the area of the building to derive a kWh/m^2/year. An example of such analysis can be seen below and represents a twenty-floor office building development in London.

Figure 3 Case Study ISO 25745-2 Energy Analysis

Category data	Symbol	Units	PL01/FL	PL02/EL	PL03	PL04	PL05	PL06	PL07/EL	PL08/FL	GL01	GL02	CL01
Category			5	5	5	5	5	5	5	5	4	4	3
Median number of trips/day for category (BS EN ISO 25745-2, Table 1)	nd		1500	1500	1500	1500	1500	1500	1500	1500	750	750	300
Total operating days per year (BS EN ISO 25745-2, Table A1)			260	260	260	260	260	260	260	260	260	260	260
Lift parameters, measurement data													
Rated load	Q	kg	1275	1275	1275	1275	1275	1275	1275	1275	2500	2500	1275
Rated speed	v	m/s	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	1.6	1.6	1
Acceleration	a	m/s^2	1	1	1	1	1	1	1	1	1	0.9	0.9
Jerk	j	m/s^3	1	1	1	1	1	1	1	1	1.2	1	1
Door times	t_d	s	5	5	5	5	5	5	5	5	5	5	5
Total travel distance	s_{rc}	m	55.3	55.3	55.3	55.3	55.3	55.3	55.3	55.3	55.3	55.3	11.85
Reference cycle energy	E_{rc}	W·h	190	190	190	190	190	190	190	190	400	400	115
Idle power	P_{id}	W	260	260	260	260	260	260	260	260	370	370	220
Standby power	P_{st}	W	200	200	200	200	200	200	200	200	280	280	200
Average trip distance	s_{av}	m	21.57	21.57	21.57	21.57	21.57	21.57	21.57	21.57	24.33	24.33	5.81
Ratio average travel (BS EN ISO 25745-2, Table 2)	k_{av}	%	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.44	0.44	0.49
Percentage rated load (BS EN ISO 25745-2, Table 3)	(%Q)	%	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	2.2	2.2	4.5
Load factor (50% balance)	k_l	%	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.96	0.96	0.93
Idle percent (BS EN ISO 25745-2, Table 4)	R_{id}	%	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.45	0.45	0.36
Standby percent (BS EN ISO 25745-2, Table 4)	R_{st}	%	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.55	0.55	0.64
Energy calculation													
Specific energy	E_{spc}	mW·h/kg·m	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.45	1.45	3.81
Running time per day	t_{rd}	h	7.14	7.14	7.14	7.14	7.14	7.14	7.14	7.14	4.72	4.77	1.07
Standing time (the time the lift is not running)	t_{nr}	h	16.86	16.86	16.86	16.86	16.86	16.86	16.86	16.86	19.28	19.23	22.93
Time to travel the average travel distance	t_{av}	h	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	22.6	22.9	12.8
Running energy/day	E_{rd}	W·h	48101	48101	48101	48101	48101	48101	48101	48101	63619	63619	7829
Standing energy/day	E_{nr}	W·h	3,798	3,798	3,798	3,798	3,798	3,798	3,798	3,798	6,180	6,164	4,751
Total energy/day	E_d	W·h	51899	51899	51899	51899	51899	51899	51899	51899	69799	69783	12580
Total energy/day		kWh/day	51.9	51.9	51.9	51.9	51.9	51.9	51.9	51.9	69.8	69.8	12.6
Total energy/year		kWh/year	13493.7	13493.7	13493.7	13493.7	13493.7	13493.7	13493.7	13493.7	18147.7	18143.5	3270.8

Total Energy/Year (kWh/yr)	147512
Area (NLA m^2)	19525
$kWh/m^2/yr$	**7.56**

Note:

1. Lift energy calculated using ISO 25745-2 (2015).
2. The reference cycle energy, idle and standby power are assumed data.
3. Total energy per year based on 5 days week.

This analysis indicates a theoretical energy consumption of 7.6 kWh/m^2/yr. The daily predicted energy consumption of the main group of eight passenger lifts is 8 x 52 = 416 kWh.

However, within the analysis are a number of significant assumptions; reference cycle energy, standby power, and idle power are all assumed for the proposed equipment. This, allied to the fact that the methodology takes no account of group control logic, or the potential benefit of regenerative drives, may serve to make the assessment of limited value, especially when considered in the real-world context of trying to accurately predict actual energy consumed for a building yet to be built.

But accurate prediction is precisely what our industry is being tasked to provide. Recent changes in legislation, combined with a market appetite to provide and occupy demonstrably energy efficient premises, are placing a growing focus on delivering buildings that perform as predicted. Initiatives such as the NABERS scheme and its associated Design for Performance (DfP) process [7] are becoming typical requirements on large commercial office buildings in the UK, and include a requirement to audit the actual real-world energy usage regularly to ensure it remains no more than that predicted. The need therefore to be able to predict energy usage more accurately is coming at us fast.

It therefore seems to the author that we might explore alternate methods of predicting energy consumed by lift systems, perhaps by utilizing existing simulation tools already to hand.

Figure 4 [8] below illustrates an established full day demand profile for a passenger lift and might be an appropriate starting point to define the demand, at least in the current absence of more real-world data from the industry.

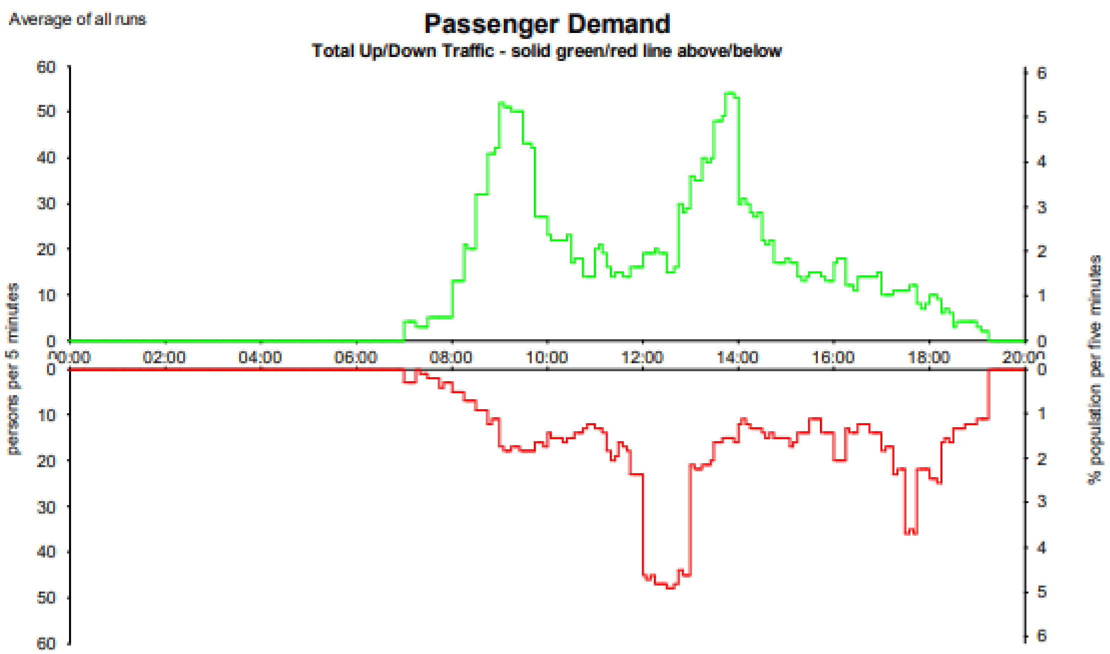


Figure 4 Siikonen Full Day (24-hr) Office Demand Template

Some lift traffic analysis software already contains energy "modules" which model the electrical characteristics of lift equipment. Figure 5 below illustrates an example of such data generated for the eight passenger lifts in this case study and shows predicted kW values for both running and standby modes along with estimates of power requirements under different loads whilst running in different directions. Figures for standby and idle are assumed and typical.

	Car 1	Car 2	Car 3	Car 4	Car 5	Car 6	Car 7	Car 8
kW drive off	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
kW drive on	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
kW 0% load Up	-6.2	-6.2	-6.2	-6.2	-6.2	-6.2	-6.2	-6.2
kW 25% load Up	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
kW 50% load Up	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8
kW 75% load Up	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9
kW 100% load Up	27	27	27	27	27	27	27	27
kW 0% load Down	21.6	21.6	21.6	21.6	21.6	21.6	21.6	21.6
kW 25% load Down	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
kW 50% load Down	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
kW 75% load Down	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5
kW 100% load Down	-9.9	-9.9	-9.9	-9.9	-9.9	-9.9	-9.9	-9.9

Figure 5 Electrical Data Input To Energy Simulation Model

It's of note that some of the running values are negative which on closer inspection indicate the system running in a regenerative capacity, essentially pushing energy back into the system. This is particularly prevalent with a light car running up when the heavier counterweight is overhauling the motor, and with a heavy car running down journey where the heavier car is overhauling the motor.

This approach seems therefore to offer some opportunity in terms of aligning the analyses with a more real-world scenario, especially when one also considers the embedding of this data in a traffic simulation tool which might also account for efficiencies in dispatching that should be inherent in smart control systems such as hall call allocation.

Running the simulation 10 times, each time with a randomized passenger demand pattern, elicits the results shown in Figure 6 below. It is very relevant to note that in building this model, the typical daily population has been set at 70% of the design population; this approach accords with the recommendations set out in NABERS.

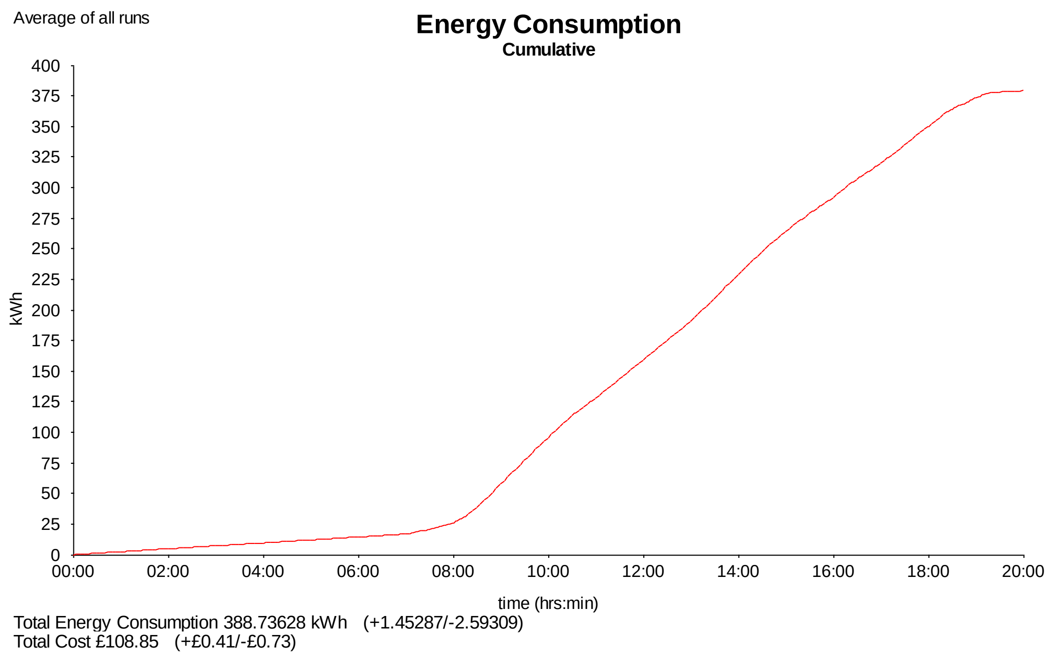


Figure 6 Simulation Model Daily Energy Use

The total daily energy consumption of the eight passenger lifts is modelled to be 389 kWh, a 6.5% reduction on the 416 kWh predicted by the ISO 25745-2 methodology.

If one reviews further the proposed 24-hour demand model it is of note that a significant period of time is spent with no or very low demand, i.e. the lifts are sat stationary in standby or idle mode. The assumed and actual kW rating of standby and idle mode are therefore very significant (particularly in residential applications where the percentage time spent stationary can far exceed that in an office). If one were to adopt a more aggressive assumption in the case study, and model say 150W idle and 200 W standby, the predicted daily energy consumption of the system falls again to 374 kWh, now a 10% reduction from the ISO modelled figure, see Figure 7 below.

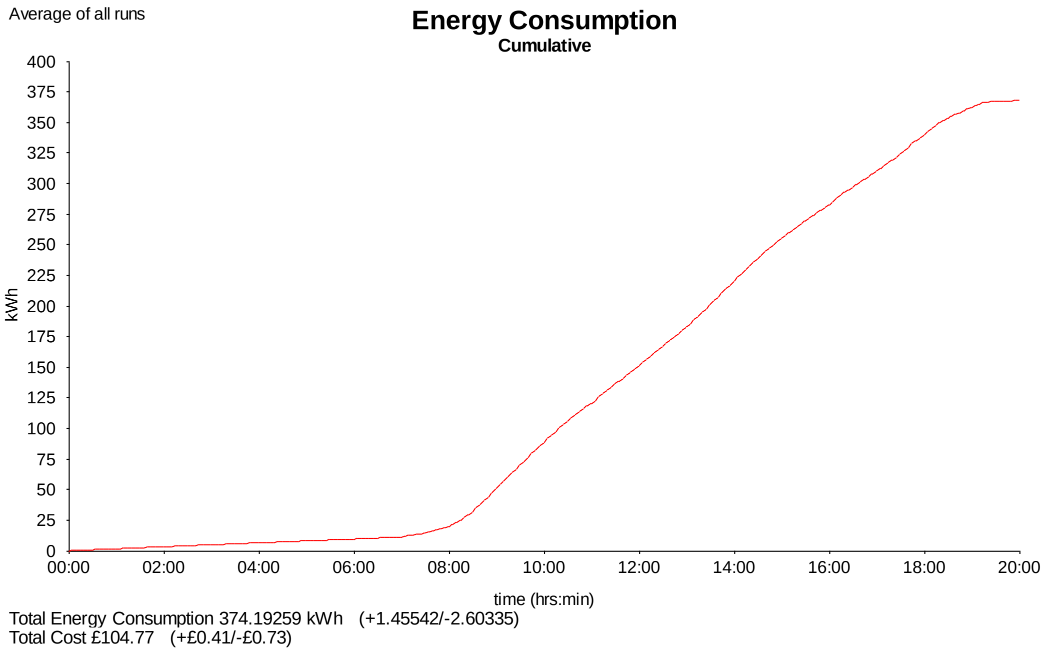


Figure 7 Simulation Model Daily Energy Use (Optimised Standby/Idle)

There is also a growing trend within office design for building amenities, aimed at attracting people back into the office. These amenities have the potential to create additional, disruptive demand on the passenger lifts, and to a lesser extent on the goods lifts. In an ideal energy model this demand would also be simulated however it is common for the type of amenity to be unknown at the time the lift system is being designed, and therefore assessing the potential impact on demand is difficult. It is suggested that in the absence of any more detailed amenity brief, a figure of 5% of the served population should be considered as travelling to and from each of the amenity floor(s) rather than the main lobby level (so called entrance bias). This demand pattern should be considered as coincident with the main morning and lunchtime peaks and modelled in an overlaid fashion to simulate the actual predicted movement of the lifts in response to the prevailing demand. A check should be done to ensure that the generated demand in people / hour is broadly aligned with the area of amenity and the likely population it can safely accommodate, i.e. if the design population limit of an amenity (and this is usually defined by the fire strategy) is 500 people, and the 5% entrance bias is generating 250 people in the lunchtime peak hour, the 5% entrance bias is probably too small and a 10% bias should be tested; if the 5% bias is generating say 450-550 people it is likely to be appropriate.

This approach too however has challenges, not least of which is what demand profile should be modelled as representative of a typical day or week, and how might this profile vary between a front-of-house passenger lift vs. a goods lift, vs. a firefighters lift (all of which form part of the energy model).

Proposing a suitable demand profile for goods lifts is harder as we do not yet have established demand data for such equipment. In the absence of more detailed demand data a constant traffic profile is proposed with demand to and from each floor proportional to the predicted population at the floor. For goods lifts there is likely to be a higher demand in the evenings as the building is cleared of the day's waste, and in the mornings dealing with deliveries. The reader's attention is drawn to a 2018 paper on goods lift demand [9] which provides further guidance on quantifying demand for goods lifts. Separate dedicated firefighters lifts are likely to have very modest demand with only occasional use; they should however be modelled. Amenity demand should be modelled as per the comments above on passenger lifts.

4 CONCLUSIONS & RECOMMENDATIONS

Buildings and the systems within them consume a significant amount of energy and are worthy of rigorous analyses and design development to reduce their WLC footprint. Predicting the energy footprint of lifts is complicated and currently founded on many assumptions and derived information. It would seem a challenge currently to accurately predict a lift's WLC, let alone be able to compare robustly solutions from different suppliers and select the lowest WLC offer.

The interpretation of EPD embodied carbon data is particularly complex and nuanced and needs careful interpretation by experienced practitioners, especially where comparisons are being drawn between two or more lift systems. The EPD process would be greatly assisted if the lift industry could further develop its EPD data and adopt a scalable approach that would allow a representative EPD for say a 1000 kg lift at 1.0 m/s over five stops to be scaled up to accurately represent say a 1600 kg lift at 1.6 m/s over 10 floors. At present energy modelers are forced to select EPD data for the closest lift configuration to that proposed, and this is often a very blunt approach.

Operational energy assessment has an established methodology in ISO 25745-2, however a complementary simulation approach should be developed to further enhance the modelling and represent more complex lift systems and demand profiles. Demand models for ancillary lifts such as goods lifts and firefighters lifts need to be developed and adopted in a consistent fashion. The modelling approach might then also allow the development of energy optimized algorithms in preference to performance optimized algorithms, and the ability to compare the relative benefits of different systems.

REFERENCES

[1] BS EN ISO 25745-2:2015 Energy performance of lifts, escalators and moving walks Part 2: Energy calculation and classification for lifts (elevators) (ISO 2015)

[2] https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2022/driest-july-in-england-since-1935 (accessed 5th September 2022)

[3] https://www.legislation.gov.uk/ukpga/2008/27/contents (accessed 5th September 2022)

[4] https://www.carbonbrief.org/analysis-why-the-uks-co2-emissions-have-fallen-38-since-1990/ (accessed 5th September 2022)

[5] https://sdgs.un.org/goals (accessed 5th September 2022)

[6]https://www.rics.org/uk/upholding-professional-standards/sector-standards/building-surveying/whole-life-carbon-assessment-for-the-built-environment/ (accessed 5th September 2022)

[7] https://bregroup.com/products/nabers-uk/ (accessed 5th September 2022)

[8] Siikonen M, Elevator Technology 10, IAEE, Israel 2000

[9] https://liftsymposium.org/9-past-events/71-9th-symposium-of-lift-and-escalator-technologies Goods Lifts. Who Needs Them? Len Halsey Canary Wharf Contractors Ltd, UK

BIOGRAPHICAL DETAILS

Adam J Scott BEng (Hons) CEng FCIBSE MIMechE

Adam started his career in the lift industry 31 years ago with Otis in London, UK. After twelve years working across construction, service, modernization, and new equipment sales, he moved into the world of consultancy with Sweco (formerly Grontmij / Roger Preston & Partners) and has subsequently worked on the design of vertical transportation systems for many landmark buildings around the world.

Adam is the current 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 2019 vertical transportation technical peer review committee. Adam is currently also the UK nominated expert for WG7 dealing with the accessibility standard EN81-70.

Overview of the Book “People Flow in Buildings”

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Keywords: Elevator; lift; escalator; passengers; people flow; batch size; calculation; simulation

Abstract. Recently a book called “People Flow in Buildings” dealing with lift traffic was published [1]. The book is based on the author’s experience and involvement in planning vertical traffic solutions and includes numerous figures and examples related to elevator and escalator design in buildings. This article highlights some of the novelties of the book including traffic measurement methods, measured results of daily traffic profiles, and passenger batch arrivals. The book also explains the modelling of traffic and validation of simulation. The ISO 8100-32:2020 standard, “Planning and selection of passenger lifts to be installed in office, hotel, and residential buildings”, is utilized in the examples. The book ends with current evacuation standards and provides examples of evacuation practices in some of the tallest buildings in the world. The present article explains the motivation and background of authoring the book and introduces some of the main findings.

1 INTRODUCTION

The author began her career with elevator traffic and control systems in 1984. At the time, a book called “Lift Traffic Analysis, Design and Control” had recently been published by Barney and Dos Santos [2], which gave an excellent and inspiring starting point to become acquainted with elevator traffic. Later, when planning vertical traffic solutions in buildings, “Vertical Transportation: Elevators and Escalators” by Strakosch [3] gave a perspective on elevator design.

In the 1980s, elevator control technology experienced a revolutionary switch from relay controls to embedded microprocessor systems. At first, the call allocation principles of the relay controls were transferred to the microprocessor systems, the first ones being in the Assembler and PLM-language. Microprocessors and PC board-based control systems offered a whole new area to apply mathematical methods in call allocation and in optimizing landing and car calls to elevators. Artificial Intelligence with learning and fuzzy logic were used to enhance the call allocation. Neural networks and genetic algorithms were applied directly in call allocation.

The benefits of having the destination keyboard already at the landing, not inside the car, was shown in two theses published by Manchester University in the 1970s [4,5]. Up-peak handling capacity could be increased by adding the passenger destination information already for the call allocation phase. At the end of the 1970s, Manchester University introduced lift traffic training courses for elevator consultants and manufacturers. The technology to move to destination control systems was not mature in the 1980s. At the beginning of the next decade, Schröder patented the first application of a destination control system, M10, which could be realized in a real-time control system [6]. The application included a description of the control principle and a keypad showing how the destination call could be given at the lobby. In this application, the destination call was immediately fixed to a car. This application was distinct from the other major elevator-control principles of the time.

Along with the advanced control systems of the 1990s, more daily people-flow profiles and traffic statistics were measured from various types of buildings, which increased the knowledge of the traffic in buildings and consequently affected elevator planning in buildings [7]. The up-peak calculation method assumed only that car calls were served sequentially. With simulations, the efficiency of group-control software could be examined by simulating different traffic situations. Up-peak, mixed lunchtime traffic and evening down-peak were typical traffic situations to be studied for office buildings. In addition, an evacuation situation could be simulated to discover the evacuation or the egress times when passengers use different transportation means in evacuation. The new ISO 8100-32: 2020 standard [8] sets the basics for how simulation can be used in vertical design and standardizes the definitions of the terms, and the inputs and outputs for the simulation. However, it still lacks standardization of the performance of elevator traffic simulators themselves.

During her work, the author has experienced this ground-breaking change in elevator control systems and vertical planning. The book “People Flow in Buildings” describes how the technology from relays to software-based systems has changed the solutions and design methods over the last 30-40 years. The book includes figures from real projects in which the author has been involved. The scenarios of future elevator solutions are the author´s own visions.

2 FIVE PARTS OF THE BOOK

The book is divided into five main subjects. The first two parts concentrate on measurement methods and statistics of people flow as well as control systems and transportation solutions in buildings. The third part summarizes elevator uppeak calculation equations, evacuation analysis and horizontal people flow. The last two parts of the book describe the simulation method and its use in elevator planning.

2.1 People flow measurement methods and results

The first part describes the estimation of population and various ways to measure people flow in buildings. In the early 1990s when the vertical people counting in elevators started, cameras were simple and did not have a memory, which hindered the use of sophisticated image-processing methods. Access control systems in buildings were not common and were not suitable for people counting at that time. For safety reasons, however, every elevator had a load-weighing device and photocell devices or a safety ray in the car door opening. The load-weighing device prevented the cars from overloading, and the photocells prevented the doors from closing when people were between the doors. With the photocell ray, the number of people passing through the door opening could be counted, but not the direction of whether a passenger was moving in or out of the car. By utilizing the two devices together, the number of entering and exiting passengers could be counted quite accurately.

A lot of information on daily passenger traffic patterns in buildings was obtained by the advanced control systems utilizing people-counting methods. Since the number of passengers travelling up and down varies from building to building, the results were not directly comparable. By scaling the passenger arrival rates to the population on the served floors, consistent data could be obtained which could be compared between different buildings. Typical daily passenger traffic profiles of various types of buildings are presented in the book. Figure 1 shows a typical daily profile of a residential building.

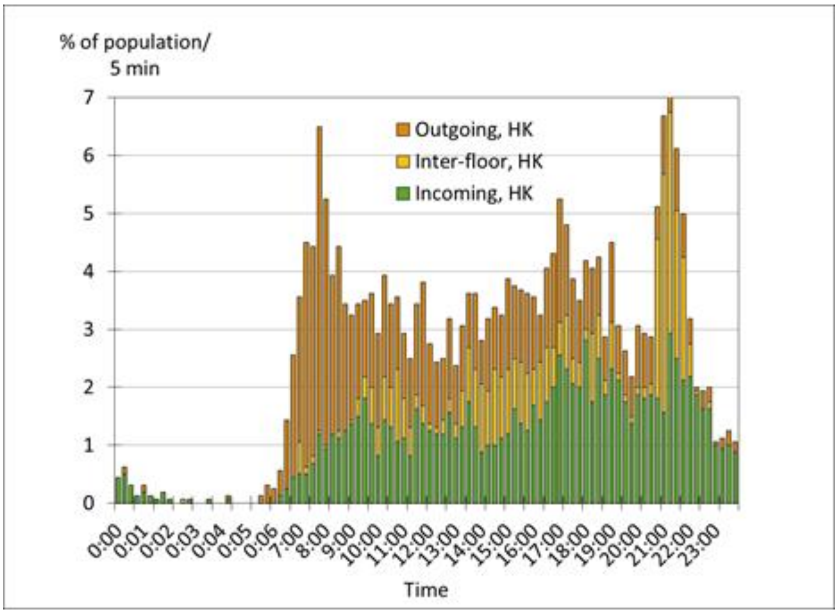

Figure 1 Daily traffic in a residential building in Hong Kong

The most recent studies reveal that people move in batches [9]. The batch sizes are the biggest in resort hotels, cruise ships, and residential buildings. In office buildings, the batch sizes are greatest during lunchtime, just when the amount of people moving with elevators is the greatest. Based on observations, rough values for the mean batch sizes in various types of buildings are proposed in Table 1. The movement in batches decreases the number of elevator stops and thus also makes the handling of lunch hour traffic easier than previously expected. If individual passenger arrivals in simulation are changed to batches, the effect should be considered in the elevator design criteria.

Table 1 Mean passenger batch size distribution for different times of a day

Type	Traffic pattern	Mean batch size
Office	**Uppeak**	1.0
	Lunch-peak	1.5
Hotel – business	**Two-way**	1.5
Hotel – resort	**Two-way**	2.0
Residential	**Two-way**	1.5
Commercial	**Two-way**	1.2
Cruise ships	**Incoming**	1.7

2.2 Solutions of vertical transportation technology

The second part of the book explains the group control principles. Two main group control principles, continuous and immediate call allocation, are explained. The operation of multi-car systems, such as double-deck elevators, Odyssey, TWIN and MULTI, are briefly described.

The manufacturers in western countries considered that the most efficient approach was the continuous call allocation principle, where the landing calls were reallocated to the best cars several times in a second. Continuous call allocation was used in the relay-based group controls and in the first software-based group controls. An existing landing call was fixed to the best car only when it was so near to the landing call floor it had to start decelerating to the floor.

The continuous call allocation principle required a lot of computing power since the number of possible ways (routes) to allocate N landing calls to a group of L elevators was N^L.

The Japanese manufacturers used the immediate call allocation principle in the first software-based systems. Here the landing call was instantly fixed after the registration to the best car. The allocated car may be delayed, and then another car may become more optimal. On the other hand, the immediate announcement of the serving car is psychologically more convenient to the passengers if they have sufficient time to approach the car. Also, the first applications of destination control were based on the direct announcement of the serving car. Immediate allocation does not require as much computing power as continuous call allocation since searching for the best car needs to be calculated only for $N \cdot L$ routes.

Mathematical methods, such as neural networks, and genetic algorithms were applied in group control systems. These methods could be applied to both immediate and continuous call allocation. With immediate control, processing power can be extended to a wider range of objectives, such as access control, horizontal navigation, and serving of passenger groups.

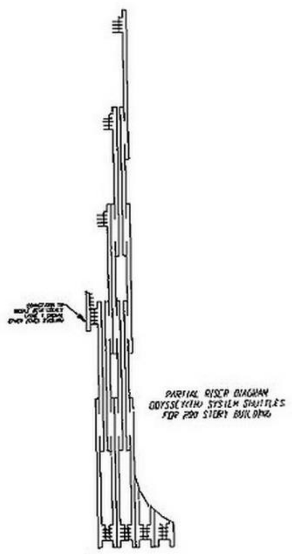

Figure 2 Odyssey system with partial riser diagram shuttles for a 200-storey building

A totally new type of control is required in Multi-Car-Elevator (MCE) systems which was considered by Barker as early as the 1990s, see Figure 2 [10]. Today, MCE systems with a linear motor have become relevant again. With MCEs, special attention must be paid to several cars moving in the same shaft [11,12,13]. The car movements should be synchronized with each other in such a way that they will not collide. Efficient loading of passengers in the lobbies should be arranged. Passenger waiting times are not such a problem as in the traction elevator systems, since the number of cabins in the shaft can be adjusted according to the need. The capacity of the cabins can be small, such as for 4-8 persons. Considering a pandemic, such as Covid-19, small cars could be better for transporting a few persons rather than large, heavy cars.

2.3 People flow calculation methods

Part 3 of the book presents the well-known elevator kinematic equations and different versions of the uppeak formulas. Vertical people-flow calculation with elevators is by far based on up-peak traffic. Several methods to calculate uppeak round trip time are presented with equal and unequal population distributions, with equal or unequal jump distances during an up trip, and with one or several entrances. Also uppeak equations for the round trip time calculation are presented for zoned elevators, for unsymmetric groups, for shuttle lifts, with double-deckers and with a multi-car systems. For the uppeak situation, passenger waiting times and queue lengths are estimated.

In addition to up-peak calculation, the round trip time for an evacuation situation as well as for passenger egress times by elevators and staircases is given. Pedestrian traffic and horizontal people flow in corridors, doorways, and walkways have their own equations and definitions, see Figure 3 [14]. The calculation part ends with handling capacity equations for escalators, moving walkways, turnstiles, ticket stations and destination operation panels.

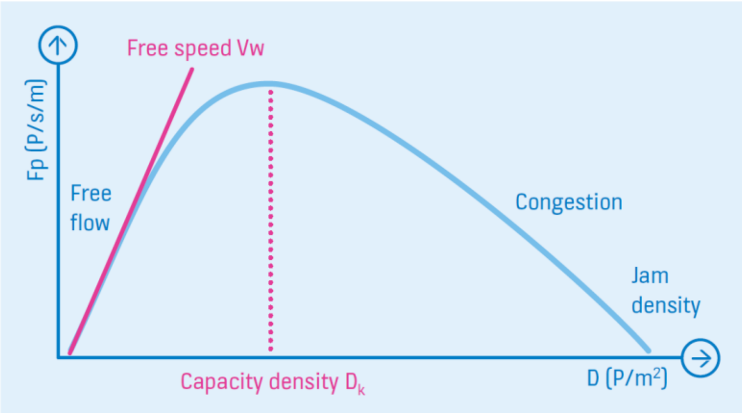

Figure 3 Relation of people flow and people density in walkways

2.4 People flow simulation

Part 4 describes first the types of elevator traffic simulators currently in use. The Monte Carlo and single-elevator group simulations are the most common ones [15,16]. In a single-elevator group, the group control system can be modelled by a generic control principle, or by a real manufacturer control software. A more sophisticated method is to simulate the traffic of the whole building with all transportation devices, not only one elevator group at a time [17]. Along with the evacuation simulation methods, modern game engines and computer hardware, pedestrian movement models have improved and these can be run in real time. The most advanced elevator traffic simulators can model both vertical and horizontal traffic in buildings.

To get a correlation between the simulation and the calculation results, elevator performance parameters were simulated with a conventional collective control system. As an example, the average round trip time and the number of starts are shown in Figure 4 as a function of passenger demand. The pure incoming and outgoing traffic, and the lunchtime traffic (40-40-20) were used. In uppeak, the carload factor of 80% is reached at about 8% passenger demand. With a higher demand than 8%, the number of starts per round trip begins to saturate and remains about constant. In addition to the car capacity, the number of starts per round trip is limited by the number of served floors. In down-peak, the number of starts per round trip can be much smaller than in up-peak. This depends on the efficiency of the control system where the minimum number of starts can be close to N/L. During lunchtime, the number of starts per round trip and the round trip time are the greatest because of heavy traffic in both directions.

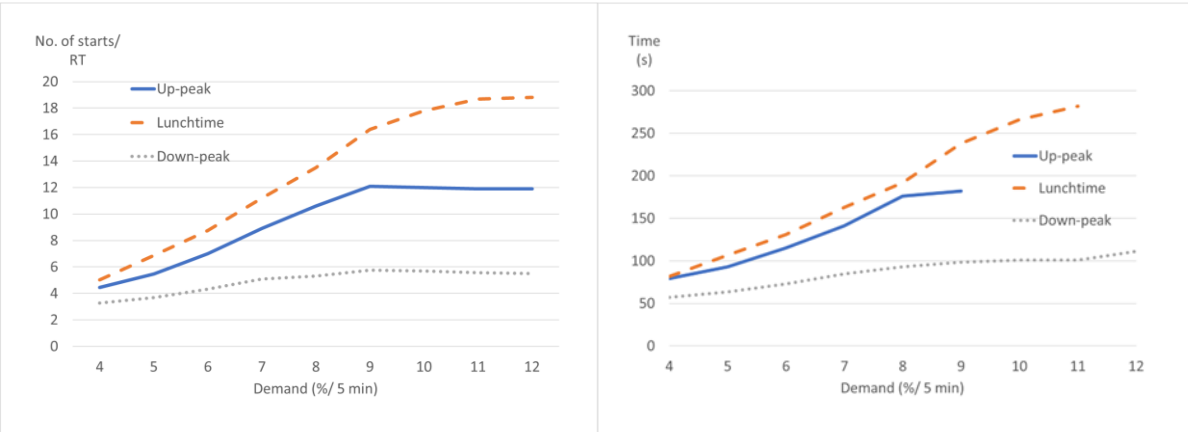

Figure 4 Elevator starts per round trip (left) and roundtrip time (right) with increasing passenger demand for a conventional control system in the example building

The ISO 8100-32:2020 standard and CIBSE Guide D:2020 define peak traffic patterns that were simulated with different group control systems and solutions: conventional and destination control systems with a single-car group and with a double-deck elevator group. The handling capacity of the system is the demand where the service times start to saturate. At saturation in office buildings, the average waiting time exceeds 30 seconds, the average time to destination exceeds 90 seconds, or the carload factor exceeds 80%. The simulated results highly depend on the building, its elevator solution and the control system, and the absolute figures cannot be used as such. Relative handling capacities of different solutions, however, are comparable in different traffic situations. The simulated handling capacities are scaled to the uppeak handling capacity of the single-car system with conventional control. According to Table 2, the relative handling capacity in a single-car lift is 1.0, and with a destination control system (DCS) it is 30% greater than with the conventional control, on average. Similarly, the handling capacity of double-deck lifts is 60 %, and that of the double-deck DCS lifts is twice the handling capacity of a single-car lift system, respectively.

Table 2 Relative handling capacities for three traffic mixes of different elevator control systems

Traffic pattern	Single-car elevator		Double-deck elevator	
	Conventional	DCS	Conventional	DCS
Up-peak	1.0	1.6	2.0	3.0
Lunchtime	1.3	1.3	1.6	2.0
Down peak	1.5	1.5	3.0	3.0
Compromise boosting	1.0	1.3	1.6	2.0

2.5 People flow planning

The last part of the book concentrates on elevator planning in tall buildings. The design criteria accurately define the upper limits for average passenger waiting times and journey times. The required number of elevators, their sizes and speeds are also defined according to the design criteria. Conventionally, the design criteria are given for uppeak when people enter the building. The CIBSE Guide D: 2020 and ISO 8100-32:2020 define waiting time design criteria also for lunchtime and two-way traffic. These are obtained by simulation. The design criteria omit the time for how fast people should exit from the building. The maximum egress time affects the required fire protection in the building and transportation devices. If the building should be evacuated within one hour, the landing doors should be at least one-hour smoke and fire resistant.

On the other hand, the final elevator arrangement in vertical planning is a compromise between several aspects: good passenger service level, the price of the solution, and the size of the selected elevator group. Typical elevator-group dimensions can be estimated according to the ISO and ANSI standards, which are shown in the book.

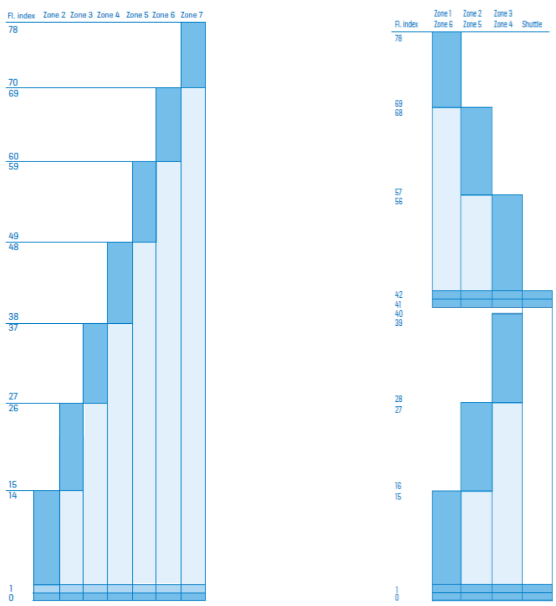

Figure 5 Elevator group arrangements of a supertall building with all lift groups starting from the ground (left), and zoning of a sky-lobby arrangement (right)

The space demand of an example elevator solution for a tall, 312-meter-high building with 10 920 persons was analyzed with six different elevator solutions. Two main elevator arrangements were selected according to the design criteria of ISO 8100-32:2020, see Figure 5. In the first solution, all lift groups start from the ground, and the other is a sky-lobby arrangement.

The relative building-space demand was analyzed with the conventional control, destination control system, with the double-deck destination control system, or with the MULTI-system. In the MULTI solution analysis, the philosophy given by Gerstenmeyer [18] was used:

1) single-car elevator groups using the conventional control
2) single-car elevator groups with the destination control system
3) double-deck groups with the conventional control,
4) double-deck groups with the destination control system,
5) sky-lobby arrangement where all elevator groups use double-deck elevators with the destination control system, and
6) sky-lobby arrangement where the local groups use double-deck elevators with the destination control system and the shuttle group uses the MULTI system

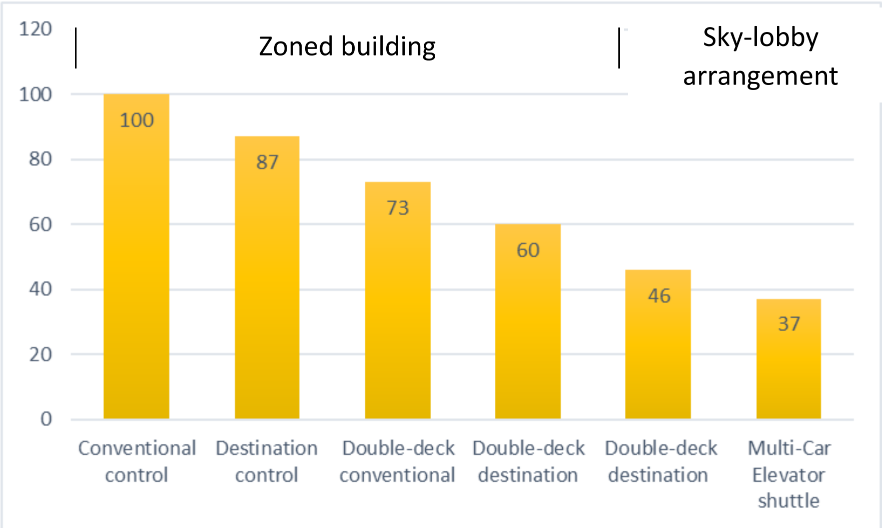

Figure 6 Elevator core space demand with different elevator arrangements

Figure 6 shows the relative space demand of each solution. The results are scaled to the space demand of case 1. The largest space is needed by the single-car elevator group with the conventional control where all elevator groups start from the ground floor. On the other hand, the sky-lobby solution with the MULTI solution in the shuttle group, and the double-deck destination control system in the local groups take only 37 % of solution 1.

With the multi-car solution, passenger waiting times are not a problem since another car moving in the same direction in the same shaft will soon serve the call. The interval and the handling capacity can be adjusted by adding the number of cabins in the shaft. Elevator speed has been the limiting factor in constructing tall buildings because of human characteristics. In the multi-car solution, the speed can be low which enables even taller buildings than today. With a multi-car shuttle, the vision of Frank Lloyd Wright of a mile-high building [19] may become a reality. On the other hand, the MCE cabins should be designed comfortable for passengers, since the passenger journey times to their destinations can become long.

3 SUMMARY

In this article, a few highlights of the book "People Flow in Buildings" were introduced. The given tables and the figures in this article are clarified in more detail in the book.

REFERENCES

[1] M-L. Siikonen, *People Flow in Buildings*. John Wiley & Sons (2021), First edition. ISBN: 978-1-119-54556-9

[2] G.C. Barney and S.M. Dos Santos, *Elevator Traffic Analysis, Design and Control*. London: Peter Peregrinus Ltd (1977). First edition.

[3] G.R. Strakosch, *The Vertical Transportation Handbook*. John Wiley, New York (1998).

[4] N. Alexandris, *Statistical Models in Lift Systems*. Ph.D. Thesis. The University of Manchester: Institute of Science and Technology (1977).

[5] G. Closs, *The computer control of passenger traffic in large lift systems.* The University of Manchester (1970).

[6] J. Schröder, "Advanced dispatching - destination hall calls + instant car-to-call assignments: M10". *Elevator World*, Vol. 38, No. 3, 40-46 (1990).

[7] CIBSE (Chartered Institute of Building Services Engineers). CIBSE Guide D: *Transportation systems in buildings*. London; UK: Chartered Institute of Building Services Engineers (2020), Sixth Edition.

[8] ISO 8100-32. *Lifts for the transportation of persons and goods – Part 32: Planning and selection of passenger lifts to be installed in office, hotel and residential buildings*. Genova; CH: International Standardization Organization (2020).

[9] J. Sorsa, M-L. Siikonen, J-M. Kuusinen and H. Hakonen, "A field study and analysis of passengers arriving at lift lobbies in social groups in multi-storey office, hotel and residential buildings". *Journal of Building Services Engineering Research and Technology* Vol. 42, No. 2, 197–210 (2021).

[10] R. Barker, "A technical primer: The Otis Odyssey system". Sao Paolo, Brazil, CTBUH, 55-76 (1997).

[11] S. Markon, H. Suzuki, K. Ikeda, and H. Kita, "Direct control of multi-car elevators with real time GA". Budapest, Hungary, *IEEE*, 191-194 (2007).

[12] J. Sorsa and M-L. Siikonen, "Double-Deck Destination Control System". *Elevatori*, Vol. 9, No. 1, 42-56 (2008).

[13] G. Thumm, "Ten years TWIN lifts". European Lift Congress Heilbronn (2012).

[14] Daamen W. *Modelling Passenger Flows in Public Transportation Facilities*. Ph.D. Delft University of Technology (2004).

[15] L. Al-Sharif, H. M. Aldahiyat and L. M. Alkurdi, "The use of Monte Carlo simulation in evaluating the elevator round trip time under up-peak traffic conditions and conventional group control". *Building Services Engineering Research and Technology*, Vol 33, No. 3, 319-338 (2012).

[16] Peters R., *Elevate^{TM} traffic analysis and simulation software.* [Online] Available at: www.peters-research.com [Accessed 6 July 2020].

[17] M-L. Siikonen, T. Susi and H. Hakonen, "Passenger traffic flow simulation in tall buildings". *Elevator World*, No. 8: 117-122 (2000).

[18] S. Gerstenmeyer and R. Peters, "Lifts without ropes: how many shafts and cars are needed". *Proceedings of the 5th Symposium on Lift & Escalator Technologies*, Northampton, United Kingdom (2015).

[19] S. Moholy-Nagy, "Frank Lloyd Wright's Testament", College Art Journal, Vol. 18, No.4, 319-329 (1959).

BIOGRAPHICAL DETAILS

Marja-Liisa Siikonen is the CEO of MLS Lift Consulting Ltd. She received her M.Sc., Lic. Sc.(Tech), and Ph.D. (Tech) in 1997 from the Helsinki University of Technology, Finland. She retired from KONE Corporation after working for 34 years with control systems and transportation planning. She has published more than 100 articles and 250 patents in the field of people flow and elevator control systems. She is the author of the book "People Flow in Buildings" published in 2021.

The Effect of Artificial Intelligence on Service Operations and Service Personnel

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Keywords: Artificial Intelligence, Machine Learning, Internet of Things, Urbanization.

Abstract. Artificial Intelligence (AI) can significantly change service operations. The timing of when service personnel are sent to lift installations and what those technicians do when on site will change. These changes are explored.

If the service tasks performed are different, one can conclude that the skill sets of the technicians will also need to be different. The skill sets and training requirements of service technicians and service supervisory personnel are also explored.

Global urbanization, post-pandemic workplace conditions, and AI will all affect the quantity of technicians required globally. These factors and their influence on staffing are reviewed.

1 INTRODUCTION

The proper functioning of lifts and the effectiveness of service operations are highly dependent on the service technician's capabilities. The technician must have the skills, tools, parts, materials, and support to properly perform service and repair functions.

Virtually all successful lift service companies, regardless of their size or location, have developed policies, practices, and procedures to deliver quality services. However, new technologies such as Machine Learning (ML), the Internet of Things (IoT), and Cloud computing will require significant changes in the service delivery system for these service providers to reap the benefits of these new technologies.

Three areas will be explored as follows:

1. The service tasks that will be performed and when they will be performed.
2. The skills and training that will be required for the next generation technician.
3. The quantity of service technicians that will be required for the post-pandemic data driven service world.

2 MACHINE LEARNING FOR LIFTS

Machine Learning involves gathering data, processing that data using algorithms and then recommending maintenance tasks and proactive actions to prevent breakdowns.

The following are some of the typical types of data used for ML [1]:

1. Static Data.
    a. Lift details such as capacity, speed, number of landings, travel, door type, drive type, and any other attribute that defines the lift.
    b. Building location.
        i. Latitude.
        ii. Longitude.
        iii. Altitude.
    c. Building type: office, residential, hotel, hospital, factory, etc.

2. Usage data.
    a. Trips made.
    b. Kilometres travelled.
    c. Door cycles per floor.
    d. Relevels.
3. Operational data
    a. Operating mode: automatic, independent service, fire service, emergency power, etc.
    b. Error codes generated.
4. Sensor data
    a. Vibration data.
    b. Ride quality.
    c. Temperature.
    d. Humidity.

The following are typical analytic tools used to evaluate data:

1. Classification And Regression Trees (CART).
2. Artificial Neural Networks (ANN).
3. Deep Learning.
4. Anomaly Detection.

3 SERVICE TASKS AND TIMING

3.1 Service Tasks

3.1.1 Present system, preventive maintenance

Most companies assign a technician a list of units to be serviced and the frequency of service for each unit. For example, units may be serviced weekly, twice monthly, monthly, or quarterly.

A specific number of hours to be spent for each visit is also included in the assignment.

A maintenance chart is commonly prepared that indicates what items should be inspected and what items should be serviced on each visit.

3.1.2 Inspecting vs. Servicing

It should be noted that inspecting, whilst it is important, leaves the lift in no better condition than it was in before the inspection.

Servicing, however, involves adjusting the component, replacing worn parts, lubricating parts, and cleaning the component. When the servicing is completed, the component should be in an as new condition.

3.2 Timing and Data Driven Maintenance

With Data Driven Maintenance, the technician is given a list of sites to visit on the next day. For each lift, a list of tasks to be performed during the visit is detailed. Most of these tasks will involve servicing a component rather than inspections.

Most inspections can be performed by using machine learning. For example, door tracks and door rollers will not be inspected if the door vibration signature is normal, and the controller has not issued any door related error codes.

If the door vibration signature indicates a contaminated landing door track at the Car Park level, which is open to the building exterior, then a service task for that door track will appear in the service task list [2].

Some maintenance tasks will be scheduled based on usage. However, usage data may be combined with environmental and building type data.

For example:

> Experience has indicated a particular type of door lock should be serviced after 15,000 cycles. Since door cycles can be counted, each floor potentially will require service at a different time. The lobby floor doors obviously need more frequent service than the doors of a partially occupied floor. Additionally, from job data it can be determined that this lift is located at a tropical seaside resort where the landing doors open to the building exterior. In such environments, doors need to be serviced every 5,000 cycles.

Breakdowns will be reduced because AI will create alerts that inform the service technician of impending failures sufficiently in advance of the failure that a visit can be scheduled to take preventive actions [3]. A scheduled repair or replacement can be performed at a lower cost than a repair that must be completed before the lift can be returned to service. All breakdowns inconvenience the client. Breakdowns that entrap passengers are especially inconvenient.

Data driven maintenance requires a far more complex maintenance scheduling system. However, such a system can deliver the proper amount of service at the proper time thereby improving both operational efficiency and customer satisfaction.

4 SKILLS AND TRAINING

Data Driven Service requires technicians and supervisory personnel that have the additional skills needed to perform this type of maintenance properly and safely. The skills required are as follows:

1. Basic mechanical, electrical, and electronic knowledge, and skills. These are the same skills currently required for lift maintenance. These basic skills are required because the lift is still performing the same functions of moving goods and people as it did before the introduction of IoT. Additionally, machine learning will not eliminate the basic oiling, greasing, and cleaning of lift equipment.
2. Computer literacy. It is logical to assume that the current and future generations of service technicians are computer and smart phone literate. However, in some markets, training in this area might be necessary.
3. Probability and Statistics. Whilst most lift service technicians are familiar with descriptive statistics, few have an appreciation of inferential statistics. Artificial Intelligence is based on inferential statistics. A basic understanding of this subject is necessary if only to appreciate that predictive analytics will always be a work in progress.
4. Vibration. The fundamentals of vibration will need to be understood. Accelerometers are being used to measure ride quality, kinematics, and to identify defective or damaged components. Important topics are:
    a. Natural Frequencies.
    b. Resonance.
    c. Fast Fourier Transforms (FFT).
    d. Vibration signatures.
5. Sensor Technology. Various types of sensors will be used to gather information that will be used by machine learning algorithms. A basic knowledge of the following types of sensors is required:
    a. Accelerometers.

   b. Barometric sensors.
   c. Temperature sensors.
   d. Humidity sensors.
   e. Strain gauges.
   f. Photo-electric sensors.
   g. Hall effect sensors.
6. Radio Frequency fundamentals. Most IoT systems are using some form of wireless communication. In addition to cellular modems for cloud connections, other low power wireless methods are being used to communicate with remote sensors. Future technicians will need to have some knowledge of the following:
   a. Frequency and Wavelength.
   b. Antenna fundamentals.
   c. Ground planes.
   d. RF cabling.
7. Electro Magnetic Compatibility (EMC). EMC fundamentals, both emissions and immunity, need to be understood. Particular attention must be given to installation methods and earthing.

5 MANPOWER REQUIREMENTS

5.1 Urbanization

Future manpower requirements will be driven primarily by urbanization.

Urbanization is the migration of people from rural areas to cities [4]. Urbanization began with the appearance of the first true cities in Mesopotamia around 5,500 BCE [5]. The technological explosion that was the Industrial Revolution led to a significant increase in the process of urbanization.

The Industrial Revolution began in the UK in the 18th century [6]. Urbanization soon followed as can be seen in the following chart:

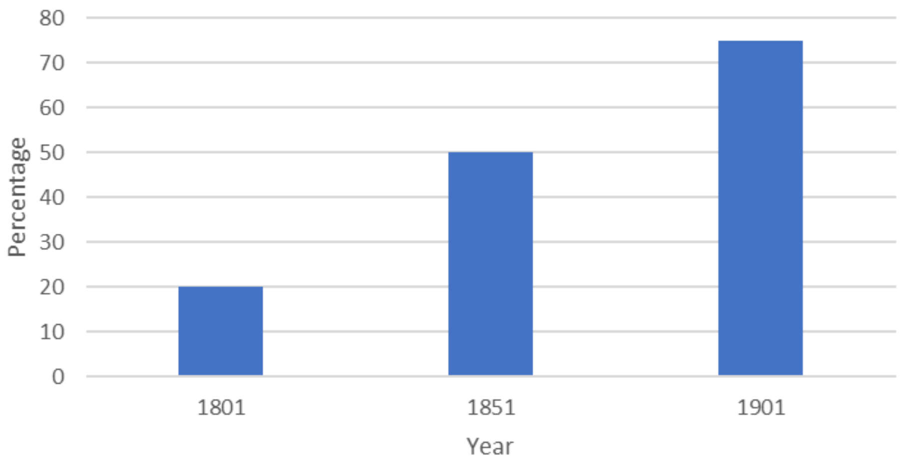

Figure 1 Urbanization Percentage

Note that the percentage of the UK population living in urban areas increased from 20% to 75% [7].

To accommodate urbanization, cities must grow upward rather than outward in order to reduce transportation time, transportation related carbon emissions, and the consumption of green spaces [8]. Upward growth implies taller buildings and more lifts.

When one thinks of urbanization one immediately thinks of China and India. In China the number of people living in cities will increase by 108 million in the next eight years [9]. In the next eight years, India will see 102 million more people living in cities [9].

Urbanization is continuing even in highly developed countries. In the next eight years, the USA will see 21.7 million more urban residents whilst urban areas in the UK will need to accommodate an additional 3.5 million people [9].

Urbanization will cause the number of lifts and the number of floors served by each lift to increase almost everywhere, even in highly developed countries.

The easy and inefficient way to deal with this additional demand for service technicians is to hire more people. The efficient way to cope with the demand is by using AI and by employing better trained technicians.

Economic data indicates that the increase in efficiency of service operations will also result in increased real wages for service technicians [10].

The number of labour hours worked for any given lift will decrease whilst the total number of hours worked in the lift industry will greatly increase due to the combined effects of increased efficiency and urbanization.

5.2 Post-pandemic working conditions

The COVID-19 pandemic will influence urbanization and office space requirements [11].

A portion of the office population will work remotely. Hybrid working, where workers work remotely a percentage of the time and work from their offices the balance of the time will be common. Remote working whether full time or hybrid will create an initial increase in office vacancy. Some of the surplus will be offset by workers requiring more individual space. Social distancing can reduce the transmission of disease whilst the additional work area improves productivity.

The effects of remote working and workers’ requirement for more personal space will only slow the rate of urbanization until the surplus space is absorbed.

6 CONCLUSIONS

Artificial Intelligence will change the timing and frequency of service. This will result in improved customer satisfaction and operational efficiency.

Lift service technicians will need additional training to acquire the skills required for Data Driven maintenance.

Urbanization will cause more lifts to be placed into service. Additional lift technicians will be needed in the immediate future as the improved labour productivity made possible by AI will not keep up with the increased demand for technicians.

REFERENCES

[1]. Smith R. The Internet of Things, Big Data, Machine Learning, and the Lift & Escalator Industry (2015) In*: Proceedings of the 5th Symposium on Lift and Escalator Technologies*, Northampton

[2]. A. Torres Perez, S. Kaczmarczyk and R. Smith, "Automatic Fault Detection and Classification in Lift Door Systems Using Vibration Signal Features". In: Rizzo, P., Milazzo, A. (eds) European Workshop on Structural Health Monitoring. EWSHM 2020. Lecture Notes in Civil Engineering, Vol 128. Springer, Cham. https://doi.org/10.1007/978-3-030-64908-1_71

[3]. Powers, A., Rudiger, C., Truax, K., Mc Carthy, M., Smith, R., *Method and Control System for Maintenance of the Door Mechanism of an Elevator System* European Patent Office. Application No. EP21720195 [online]. Available at: https://register.epo.org/application?number=EP21720195 [Accessed 06 June 2022]

[4]. *Urbanization* Available from: https://en.wikipedia.org/wiki/Urbanization. Last accessed: 04 June 2022

[5]. *Which city is considered to be the oldest in the world* Available from: https://www.discovermagazine.com/planet-earth/which-ancient-city-is-considered-the-oldest-in-the-world. Last accessed; 02 June 2022

[6] *Industrial Revolution* Available from: https://en.wikipedia.org/wiki/Industrial_Revolution Last accessed: 03 June 2022

[7] *Impact of the industrial revolution* Available from: https://www.britannica.com/topic/urbanization/Impact-of-the-Industrial-Revolution Last Accessed 05 June 2022

[8] *Urban development and Building Height Guidelines* Available from: https://www.gov.ie/en/publication/93d22-urban-development-and-building-height-guidelines-ud-bhg-2018/. Last accessed: 31 May 2022

[9] *Country Profiles* Available from: https://population.un.org/wup/Country-Profiles/. Last accessed: 01 June 2022

[10] *Understanding the Labor and Productivity Gap* Available from: https://www.bls.gov/opub/btn/volume-6/pdf/understanding-the-labor-productivity-and-compensation-gap.pdf Last accessed: 05 June 2022

[11]. *Reimagining the office* Available from: https://www.kone.com/en/Images/Reimagining-the-Office_FINAL_100dpi_tcm17-104272.pdf. Last accessed: 06December 2021

BIOGRAPHICAL DETAILS

Rory Smith is Visiting Professor in Engineering/Lift Engineering at the University of Northampton and a Consultant at Peters Research Ltd. He has over 53 years of lift industry experience during which he held positions in research and development, manufacturing, installation, service, modernization, and sales. His areas of special interest are Machine Learning, Traffic Analysis, dispatching algorithms, and ride quality. Numerous patents have been awarded for his work.

New Evidence on Lift Passenger Demand in High-Rise Office Buildings

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Keywords: lift, passenger demand, peak traffic patterns, people flow data, automated passenger counts, office buildings.

Abstract. The planning and selection of passenger lifts for a prospective building relies on requirements on peak traffic patterns, which are usually expressed by peak passenger demand in conjunction with a traffic mix. These requirements mostly determine the size of the lift installation and should therefore be realistic to ensure proper passenger service without excess capacity during the whole life cycle of the building. Despite their importance, real-world surveys on peak traffic patterns are still scarce in literature. In such surveys, human observers typically record passenger demands, but an automated method is required to obtain data on a larger scale and to contest the current requirements.

This paper proposes an algorithm that automatically recognizes peak periods occurring in an office building during a day from people flow data, as well as computes peak passenger demands and traffic mixes for the peaks. The challenge is first to recognize the start and end time of a particular peak period, and second, to scale the observed peak demand to the actual population using the lifts during the day. The scaling is crucial when comparing the measured peak demand to the required peak demand, which is usually expressed as a percentage of population.

The procedure is developed using measurements of two lift groups in a high-rise office. It is then applied to measurements from other offices to recognize trends in peak traffic patterns. The observed results are then contrasted with the current requirements for planning and selecting lift configurations.

1 INTRODUCTION

Surveys on lift passenger demand in existing high-rise buildings are still scarce in literature, which may reflect the effort required to manually count people. The first results were obtained in the 1960s by observing people arriving at or leaving lift lobbies, which, however, only reveals incoming and outgoing traffic [1]. An observer travelling in a lift car can also count interfloor traffic [2]. A large-scale study of lift passenger demand, however, requires automated methods. Large amounts of people flow data can be collected, e.g., by a lift control system or a temporary sensor mounted in a lift with human detection algorithms [3,4].

In the case of office buildings, design standards set requirements on both morning uppeak and midday lunch traffic [5,6,7]. The lift configuration is required to have a handling capacity that at least matches with assumed peak passenger demand to avoid congestion and extensive waiting times. In complex cases, the lift configuration is simulated with a specified traffic mix that defines the proportions of incoming, outgoing and interfloor traffic. Hence, people flow data from existing buildings provide important feedback for planning new buildings. To enable the processing of large-scale data, this paper develops an algorithm to automatically recognize morning uppeak, midday lunch-peak and evening downpeak periods from people flow data. The algorithm is applied to a unique data set of 25 offices around the world to find trends in peak traffic patterns.

The rest of the paper is organised as follows. Section 2 introduces methodology to collect people flow data, i.e., building population and lift passenger demand, from automated counts of boarding and alighting lift passengers. Section 3 describes the algorithm to automatically recognize peak periods in offices using people flow data. The algorithm is used to capture peak traffic patterns (Section 4), which are compared to the requirements used in the planning and selection of a lift configuration (Section 5). Section 6 concludes the paper.

2 AUTOMATIC COLLECTION OF PEOPLE FLOW DATA

Boarding and alighting lift passengers can automatically be counted either by a lift control system or by a temporary sensor mounted in a lift. The counts recorded during an office day lead to two important data points that characterize people flow in the building, namely, the population of daily lift users and lift passenger demand throughout the day. As the counts consider passengers transferring to and from a lift, passengers waiting in the lobby are invisible before they step in. Therefore, the counts lag the true passenger arrival times at the lobby. The lag may become significant if waiting passengers do not fit in a lift but need to wait for the next one. Therefore, in lift groups, where peak passenger demand exceeds its handling capacity, true peak demands could even be higher than recorded this way.

In the following, these concepts are concretised by showing data from an office building located in Singapore. The data was collected by temporary sensors that are capable of identifying boarding and alighting passengers with greater than 95% accuracy [4]. The building has 22 office floors above the main entrance floor and three underground levels for car parking, which are also considered as entrance floors. The office floors are split into two sets of consecutive floors, the Low- and the High-rise, both of which are served by a group of four lifts.

The number of people inside the building (within a particular rise) at any time of the day is defined as the cumulative difference of lift passengers boarding and alighting on entrance floors. For the sake of clarity, the building (rise) is assumed empty if the cumulative sum appears negative, i.e., for some period, the number of outgoing passengers exceeds the number of incoming passengers and people already inside the building (rise). The negative number of people inside can arise from stair usage, incorrect passenger counts, or counting started when some people were already inside. The population of daily lift users can be defined as the maximum number of people inside the building (rise) during the day [2].

Fig. 1 shows the cumulative number of people inside the building. In both rises, maximums occur at about 11 o'clock while about 90% of occupants had arrived by 9:30. The data implies that population in the Low-rise was 279 persons while it was 635 persons in the High-rise on the day of collecting the data. Hence, the Low-rise was much less densely populated than the High-rise.

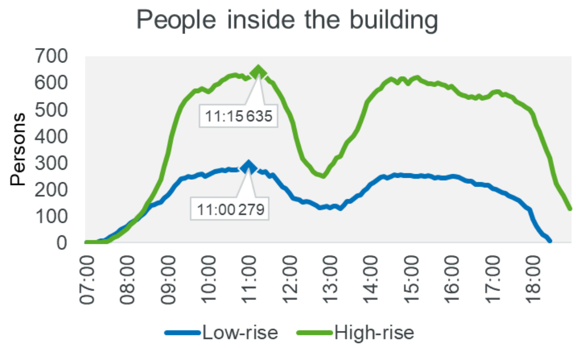

Figure 1 Building population throughout the day in both rises

Lift passenger demand can be divided into its components: incoming, outgoing and interfloor traffic. Passengers boarding a lift on entrance floors form incoming traffic while passengers alighting a lift on entrance floors belong to outgoing traffic. Interfloor traffic occurs between populated floors. It comprises passengers boarding a lift on a populated floor and travelling upwards as well as of passengers travelling downwards and alighting a lift on a populated floor.

In lift traffic planning, passenger demand is usually expressed as a percentage of population per five minutes [5,6,7]. The planning of office lifts is based on requirements that are set on this percentage passenger demand. Hence, the observed percentage passenger demands can be contrasted with the current design criteria given in standards and guidelines. It is worth noticing the difference between the observed population in an operational building and design population of the standards and guidelines, which designate a maximum for which a building is being designed [5].

Fig. 2 demonstrates percentage passenger demand throughout the day in both rises. In the charts, incoming, outgoing and interfloor passenger demands are stacked on top of each other. These daily traffic profiles show striking differences considering that they are observed in the same building. The Low-rise clearly represents an office with multiple tenants where peak traffic patterns are spread over a long period and interfloor traffic is almost non-existent. Conversely, the High-rise exhibits characteristics of a single-tenant office: demand peaks are sharp and the proportion of interfloor traffic is high especially during lunch-peak. Furthermore, peak demands in the High-rise are much higher than in the Low-rise.

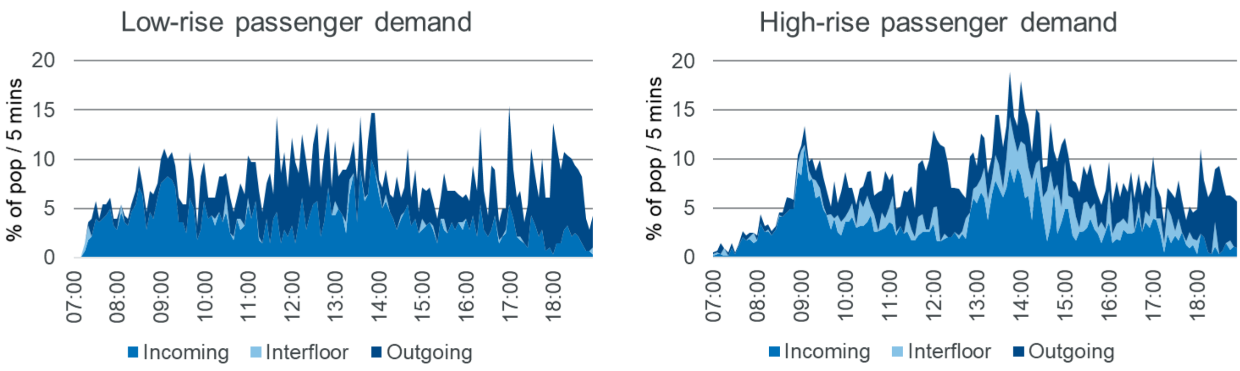

Figure 2 Percentage passenger demand in the Low-rise (left) and in the High-rise (right)

3 RECOGNITION OF PEAK TRAFFIC PATTERNS FROM PEOPLE FLOW DATA

Peak periods in offices occur typically in the morning, around midday and in the evening. In the following, a method to recognize them from people flow data is described using the data of the office building in Singapore described above. As could be seen in Fig. 2, traffic mix and passenger demand vary from interval-to-interval characteristic to the rise. Therefore, general rules to automatically recognise peak periods and underlying traffic patterns cannot only rely on the observed traffic mixes and passenger demands. Especially in the case of the High-rise, traffic mixes vary significantly between five-minute intervals. Hence, five-minute intervals are too random for a reliable algorithm to recognize peak conditions, which benefits from a rather stable traffic mix and passenger demand. Therefore, peak period recognition is carried out in 15-minute intervals.

Fig. 3 shows the Low- and the High-rise traffic mixes as stacked proportions of incoming, outgoing and interfloor traffic in 15-minute periods throughout the day. The figure also contains a line that helps to detect when the proportion of incoming or outgoing traffic exceeds 50%. In the morning, incoming traffic is predominant as people arrive at work and travel from entrance floors to populated floors where their workplaces are located. Around midday, office workers first go for lunch and then come back to their workplaces. If restaurants are located on an entrance floor or people exit the building through an entrance floor to have lunch, people flow is predominantly outgoing in the beginning and incoming at the end of the lunch-peak period. Typical to lunch-peak period, a significant portion of people may also travel to the direction opposite to the predominant direction as well as between the populated floors. In the evening, people exit offices through entrance floors, which results in predominantly outgoing traffic.

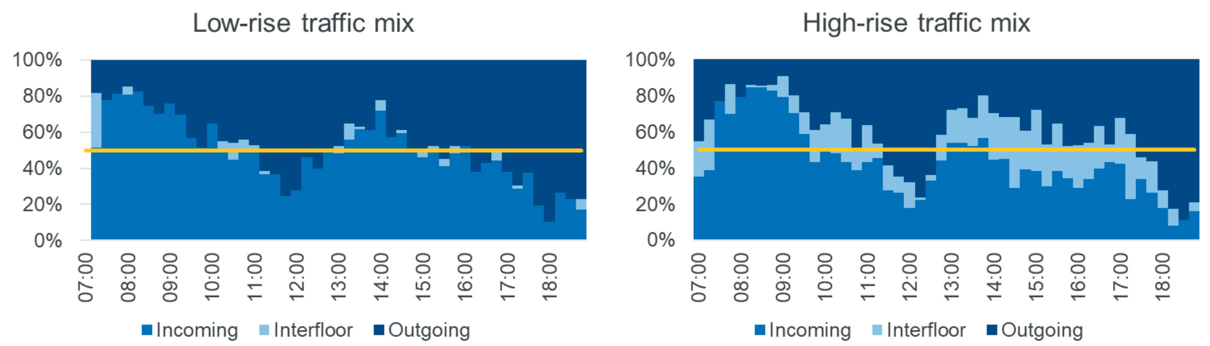

Figure 3 The Low- and the High-rise traffic mixes throughout the day

During peak periods, passenger demands vary from interval to interval as shown in Fig. 4 for 15-minute periods. Peak passenger demands for morning uppeak and midday lunch-peak are clearly distinct from the off-peak demand, which varies around 7% of population per five minutes. However, evening downpeak in the High-rise does not rise above the off-peak level although the Low-rise exhibits a clear peak.

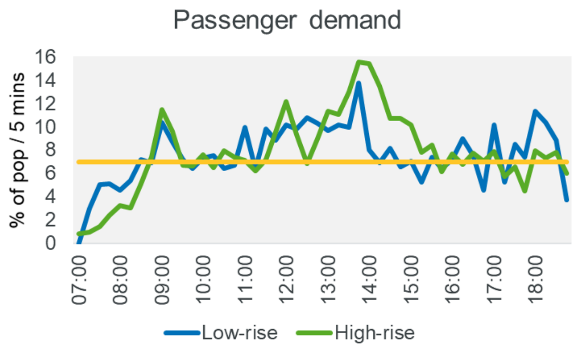

Figure 4 Passenger demand in the Low- and the High-rise with a helpline at 7% / 5 min

3.1 A method to recognize peak periods

A traffic forecaster based on fuzzy logic, originally developed to recognize traffic patterns in a real-time control system, can be applied to the problem at hand [3]. Fuzzy logic allows classification of a continuous range of values between zero and one by descriptive terms [8]. For example, given a proportion of a traffic component, fuzzy logic infers whether the proportion is *Low*, *Medium* or *High*. Specific rules first convert the descriptive proportions into more generic types such as *Incoming*, *Outgoing*, *Two-way*, and *Mixed* traffic. It is worth noticing the duplicated use of terms incoming and outgoing: in this context, they mean generic traffic type, not traffic components as parts of a traffic mix. Second, fuzzy logic identifies passenger demand to be *Light*, *Normal*, *Heavy*, or *Intense* with respect to the peak five-minute demand of the prevailing peak period.

During morning uppeak periods, the proportion of incoming traffic follows the same pattern in both rises as shown in Fig. 3. Traffic mixes exhibit significant proportions of incoming traffic already after 7:15 in both rises but that does not necessarily designate early beginning of uppeak period. Indeed, the traffic forecaster interprets passenger demands light until 7:30 in the Low-rise and until 8:30 in the High-rise. As shown in Fig. 4, passenger demand exceeds 5% of population per five minutes during the interval of 7:30-7:45 for the Low-rise and 8:30-8:45 for the High-rise. Traffic patterns during these intervals are then classified as normal incoming traffic, which marks the beginning of uppeak period. Uppeak period ends in the Low-rise at 9:30 since the traffic forecaster interprets the traffic mix between 9:30 and 9:45 as Two-way. This follows from the proportions of incoming and outgoing traffic, 56.7% and 43.3%, respectively, which are on Medium level according to the fuzzy membership functions used by the traffic forecaster. On the other hand, traffic in the High-rise is still detected as Normal Incoming between 9:30 and 9:45 since 59.0% of incoming traffic is classified as Medium but 29.0% of outgoing and 12.0% of interfloor traffic as Low.

In the beginning of lunchtime, say, before 12 o'clock, the proportion of outgoing traffic is more than 50% in both rises. After 12:00, the proportion of outgoing traffic decreases steadily while the proportion of incoming traffic increases reaching 50% at about 13:00. As shown in Fig. 4, passenger demand is high throughout the lunch-peak period. The Low-rise demonstrates a clear peak only at the end of the period but the High-rise during both the outgoing and the incoming phase. Hence, peak detection is not necessarily as clear as it is in the case of morning uppeak. The lunch-peak is defined to begin when the traffic forecaster classifies 15-minute traffic pattern as Outgoing with at least Normal intensity, which results in start times of 11:15 and 11:30 for the Low- and the High-rise, respectively. The outgoing phase continues as long as a 15-minute traffic pattern remains either predominantly Outgoing or Two-way with a proportion of at least 50% of outgoing traffic component. In a similar manner, the incoming phase of the lunch-peak can be detected when two-way traffic contains more than 50% of incoming traffic or the traffic pattern is recognized as Normal Incoming. With these definitions, the lunch-peak in the Low-rise lasts until 15:00 while it ends in the High-rise at 14:30.

In the afternoon, the proportion of outgoing traffic exceeds 50% in the Low-rise already at 15:30 (Fig. 3). After the initial peak, the proportion of outgoing traffic decreases below 50% just to return above 50% between 16:15 and 16:30. Furthermore, passenger demand in the Low-rise drops to a low level just before 17:00 while the highest five-minute peak demand occurs just after 17:00 as can also be seen in Fig. 4. On the other hand, the proportion of outgoing traffic in the High-rise rises above 50% at 17:30, but the traffic forecaster recognizes a traffic mix consisting of 29% incoming, 48% outgoing and 23% interfloor traffic between 16:00 and 16:15 as predominantly Outgoing. Since passenger demand during that period is rather high, downpeak is found to start at 16:00 in the High-rise even though the highest peak demand occurs after 18:00. Thus, both rises exhibit a pattern of recurring and relatively short peak periods. To detect the highest peaks, all periods satisfying downpeak criteria need be included in the overall evening downpeak period.

3.2 Peak traffic patterns

Once the beginning and the end of peak periods have been determined, it is time to define peak traffic patterns. Table 1 and 2 show passenger demands as well as traffic mixes aggregated for different period lengths for the Low- and the High-rise, respectively. Average passenger demands across the entire peak periods are clearly lower than the demands in shorter periods as can be expected. The 15-minute average peak demands clearly flatten the highest five-minute peak demands showing extreme values.

Even though five-minute demands are somewhat affected by randomness, they well describe worst-case passenger demands. Regardless of the differences, the rises seem to indicate similar timing of the most intense peaks, which may reflect the culture and way of life in Singapore. In the morning, passenger demand peaks just after 09:00, midday outgoing traffic peaks are around 12:00, and evening downpeak around 18:00. Peak demands during morning uppeak conform well with the known design criteria for multi- and single-tenant offices being 11.1% of population per five minutes for the Low-rise and 13.4% for the High-rise. Typical to office buildings, the highest demand peaks during lunch traffic clearly exceed the uppeak demands and occur during the incoming phase: 14.7% in the Low-rise and 18.9% in the High-rise. Interestingly, the highest five-minute demand of the day in the Low-rise occurs during downpeak at 17:00 and reaches as high as 15.4%. Clearly, this peak as well as the other extreme downpeak demand occurring at 18:00 show that a significant amount of office workers end their days exactly on the hour. On the other hand, downpeak demands in the High-rise are clearly on a lower level compared to other peak periods, remaining at 11.0% at 18:00.

Table 1 Low-rise peak traffic patterns aggregated for different period lengths

Peak	Period	Demand [% / 5 mins]	Incoming [%]	Outgoing [%]	Interfloor [%]
Uppeak	7:30-9:30	6.7	76.6	22.8	0.6
	9:00-9:15	10.4	76.0	24.0	0.0
	9:05-9:10	11.1	71.0	29.0	0.0
Lunch-peak outgoing	11:15-13:15	9.4	37.2	62.5	0.3
	11:30-11:45	9.8	36.8	63.2	0.0
	11:40-11:45	14.3	32.5	67.5	0.0
Lunch-peak incoming	13:15-15:00	9.1	59.6	37.8	2.6
	13:45-14:00	13.7	61.3	38.7	0.0
	13:50-13:55	14.7	68.3	31.7	0.0
Downpeak	15:30-18:45	8.0	34.6	64.2	1.2
	17:00-17:15	10.2	38.1	61.9	0.0
	17:00-17:05	15.4	34.9	65.1	0.0

Table 2 High-rise peak traffic patterns aggregated for different period lengths

Peak	Period	Demand [% / 5 mins]	Incoming [%]	Outgoing [%]	Interfloor [%]
Uppeak	8:30-9:45	8.1	75.3	17.3	7.4
	9:00-9:15	11.5	79.5	9.3	11.1
	9:05-9:10	13.4	85.9	14.1	0.0
Lunch-peak outgoing	11:30-13:00	9.0	25.4	66.3	8.2
	12:00-12:15	12.1	17.9	68.0	14.1
	12:00-12:05	12.9	26.8	61.0	12.1
Lunch-peak incoming	13:00-14:30	13.3	51.0	28.1	20.9
	13:45-14:00	15.5	56.4	19.9	23.7
	13:45-13:50	18.9	48.3	24.2	27.5
Downpeak	16:00-18:45	7.0	28.1	55.0	17.0
	18:00-18:15	7.9	18.0	72.4	9.7
	18:05-18:10	11.0	21.4	78.6	0.0

Peak traffic patterns are characterized by specific traffic mixes that represent typical traffic conditions during the periods. The proportion of incoming traffic is surprisingly low, only about 75%, for the whole uppeak period in both rises. As already indicated by Figs. 2 and 3, the Low-rise does not have significant amounts of interfloor traffic even during lunch-peak. The High-rise, on the other hand, has interfloor traffic throughout the day end even more than 20% during the period of the most intense lunch-peak.

4 PEAK TRAFFIC PATTERNS IN HIGH-RISE OFFICE BUILDINGS

Measurements with the temporary sensor devices were conducted in 25 high-rise offices from 2018 to 2020 in different regions. Data was collected before pandemic-related restrictions in the respective cities and countries. The sample includes 12 cases from Asia, two from Australia, eight from Europe and three from North America. The European cases include buildings from different parts of Europe: the Netherlands, Poland, Spain, Serbia, and Turkey. All the Asian cases are from Southeast Asia: Singapore, Thailand, Malaysia, and the Philippines. North American cases are from different parts of the USA.

From each building, a random measurement day was chosen. It does not necessarily present the most typical day nor the busiest day of the building. Buildings that had relatively low peak demands during measurement days might have higher peaks on other days, and vice versa. The only reason for rejecting a measurement day was missing data. In such a case, another day was chosen. Late evening hours after evening downpeak are not critical, but the morning hours are: if recording was started too late or if some sensor missed early morning, population would be estimated lower than in reality and, consequently, percentage passenger demand higher than in reality would be observed.

As shown in Section 3, lunch-peak may nicely split into downpeak and uppeak phases. However, it turns out that, in only half of the cases, these phases are clear. In the rest of the cases, either the phases are not recognisable, or they repeat due to lunch shifts. As a result, the detection of lunch-peak period became non-trivial, and the highest peaks could not clearly be determined. Therefore, the following analysis considers lunch-peaks as continuous peak periods rather than in phases.

4.1 Office categorization based on lunch-peak interfloor traffic proportion

Often offices can be recognized as single or multi-tenant offices based on peak passenger demands and proportions of interfloor traffic. Well known examples are Siikonen profiles [3]. By using only measurement data but no a priori knowledge of the studied offices, peak demands did not show any clear trend. Therefore, buildings are categorised into offices with low, medium, and high interfloor traffic, where the proportion of interfloor traffic during lunch-peak was less than 15%, between 15% and 30%, and more than 30%, respectively. The interfloor category does not directly indicate office type, but buildings with low interfloor proportion are probably multi-tenant offices. Buildings with medium interfloor proportion are often single-tenant offices, but some of them can also be multi-tenant offices. Buildings with high interfloor proportion have either a transfer or an attraction floor with, e.g., cafeterias, restaurants, meeting rooms, conference facilities, or social space, among populated floors. Such buildings cannot automatically be identified as a single- or a multi-tenant office. Table 3 shows the number of measured offices for each region and interfloor category.

Table 3 The number of measured offices for different regions and interfloor categories

Interfloor category	Asia	Australia	Europe	North America	Total
Low (<15 %)	5	2	2	1	10
Medium (15…30 %)	5	0	1	2	8
High (≥30 %)	2	0	5	0	7
Total	12	2	8	3	25

Table 4 shows average interfloor proportions for different peak periods as well as the upper bounds of their 95% confidence intervals. The averages for lunch-peak follow the above categorisation: 8.6% for the low, 21.9% for the medium, and 41.0% for the high interfloor category. The upper bounds of 95% confidence intervals interestingly show how high the proportion of interfloor traffic can be, the most distinguished case being the lunch-peak of the high category with as much as 50% interfloor traffic. Offices in the low category also had low interfloor proportion during morning uppeak and evening downpeak. The buildings in the medium and high category had a lot of interfloor traffic during uppeak and downpeak, slightly more than 20%. In general, the proportion of interfloor traffic was about the same during all peak periods within an interfloor category. As an exception, lunch-peak interfloor traffic proportion in the high category was about double compared to other peak periods. In a couple of cases, interfloor traffic was almost non-existent all day: both Australian cases and the example Low-rise from Singapore.

Table 4 Peak period interfloor traffic proportion per interfloor category

	Average interfloor proportion (%)				95% CI UB interfloor proportion (%)			
Peak period	**Low**	**Medium**	**High**	**All**	**Low**	**Medium**	**High**	**All**
Uppeak	7.6%	23.2%	20.2%	16.2%	11.3%	29.4%	29.6%	20.4%
Lunch-peak	8.6%	21.9%	41.0%	21.9%	12.0%	25.3%	49.6%	28.0%
Downpeak	10.3%	21.6%	22.2%	17.2%	15.0%	25.7%	32.1%	21.1%

The analysis of regional differences would also have been interesting but is omitted here. The offices are unevenly distributed among different interfloor categories within the regions. This entails a risk that, e.g., single-tenant offices from one area are compared to multi-tenant offices from another. Therefore, with this sample, results based on regions would be misleading. With a larger sample of office buildings from each region, the analysis could be expanded to cover regional differences within an interfloor category.

4.2 Peak demands in offices

Table 5 shows statistics for the highest peak demands across the studied buildings. Minimums, maximums, averages and 95% confidence intervals are given for each peak period and interfloor category separately. Generally, in 72% of measured offices, the highest peak occurred during lunch-peak, in 12% of the cases during morning uppeak, and in 16% of the cases during downpeak. Minimums and maximums well demonstrate the wide range of observed values. Furthermore, maximum demands, while possibly being random events, reveal the extremes that lift installations may encounter: 15.3% of population per five minutes in morning uppeak, 23.2% in midday lunch-peak and 19.0% in evening downpeak.

The averages and the upper bounds of 95% confidence intervals are more important than the extremes when contrasting the actual peak demands to the requirements in design standards. The average of highest morning uppeak demands was 10.7% of population per five minutes, which seems similar to peak demands in the Peters major office and in the Siikonen multi-tenant office measurement [2,3]. The upper bounds of 95% confidence interval exceed these measurements but matches quite well with the highest uppeak demand in the Siikonen single-tenant office measurement.

The most intense five-minute demand during lunch time was on average 12.8% and its 95% confidence interval upper bound was 14.2%. These values match well with the corresponding peak demands in the Peters major office and Siikonen single-tenant office. However, one Southeast Asian case had very high peak demand, 23.2% / 5 mins. Furthermore, it was not the only case with very high demand. The second highest lunch-peak demand in Southeast Asian offices was 18.9%. The same buildings that had the highest lunch time peaks had also the highest morning peaks, although the morning peaks were closer to the expectations.

Table 5 Five-minute peak demand statistics for peak periods and interfloor categories

Peak period	Interfloor category	Percentage passenger demand (% of pop / 5 min)			
		Min	Max	Average	95% CI
Uppeak	All	7.3	15.3	10.7	[9.9, 11.6]
	Low	8.6	15.3	11.4	[10.1, 12.7]
	Medium	7.9	13.4	10.4	[8.7, 12.1]
	High	7.3	13.9	10.2	[8.1, 12.3]
Lunch-peak	All	8.3	23.2	12.8	[11.4, 14.2]
	Low	9.7	16.8	13.3	[11.6, 15.1]
	Medium	8.3	18.9	12.4	[9.6, 15.2]
	High	8.9	23.2	12.6	[8.0, 17.1]
Downpeak	All	5.4	19.0	10.3	[8.9, 11.8]
	Low	6.6	15.4	11.5	[9.4, 13.6]
	Medium	6.8	16.4	9.6	[7.1, 12.1]
	High	5.4	19.0	9.5	[5.2, 13.8]

Evening downpeak is not considered in the current requirements of design standards [5,6,7]. In the previous measurements, evening downpeak demands were less sharp and clearly lower than morning uppeak and lunch-peak demands [2,3]. Therefore, downpeak has not been seen as a critical peak period in offices. From this perspective, most of the measured offices in this study resemble the earlier results where downpeak demands were clearly lower than uppeak demands. However, the highest measured evening downpeak demand was 19% per five minutes, which indicates that evening downpeaks can be intense as evidenced in early observations [1]. Average peak demand and the upper bound of its 95% confidence interval were almost the same as in uppeak, 10.3% and 11.8%, respectively, which are clearly affected by a few extremely high downpeak demands. Generally, offices in Europe had the lowest downpeak demands except for Turkish cases.

4.3 Traffic mixes in offices during peak periods

Peak period average traffic mixes are presented in Table 6 for each interfloor category. In the studied buildings, the proportion of incoming traffic in the morning was rather low, from 60% to 70% depending on the interfloor category. Generally, average traffic mixes in the interfloor category *low* closely correspond to the traffic mix of Siikonen multi-tenant office measurement [3]. For such cases, a traffic mix consisting of 70% incoming, 20% outgoing and 10% interfloor traffic could represent a typical office. However, buildings in the interfloor categories *medium* and *high* had as much as 20% interfloor traffic in the morning resembling Siikonen single-tenant office measurement. All the observed proportions of interfloor traffic clearly exceed the ones in Peters major office measurement [2].

During lunch traffic, the proportions of incoming and outgoing traffic were almost equal with respect to each other, but the proportion of interfloor traffic varied depending on the interfloor category. In the buildings in the low and the medium interfloor category, average lunch traffic mixes were close to the ones found in earlier measurements: 45% incoming, 45% outgoing and 10% interfloor traffic, or, 40% incoming, 40% outgoing and 20% interfloor traffic [2,3]. The buildings in the high interfloor category had about 40% of interfloor traffic, which is similar to Siikonen single-tenant office measurement.

Table 6 Average traffic mixes for peak periods and interfloor categories

Peak period	Interfloor category	Proportion of traffic component (%)		
		Incoming	Outgoing	Interfloor
Uppeak	All	66.7	17.1	16.2
	Low	71.3	21.0	7.6
	Medium	59.9	16.9	23.2
	High	68.0	11.7	20.2
Lunch-peak	All	39.9	38.2	21.9
	Low	47.5	43.9	8.6
	Medium	40.6	37.5	21.9
	High	28.3	30.7	41.0
Downpeak	All	21.2	61.5	17.2
	Low	25.7	64.1	10.3
	Medium	21.8	56.6	21.6
	High	14.3	63.5	22.2

As was the case with uppeak incoming traffic proportion, downpeak contains surprisingly low amount of outgoing traffic, only about 60%. The proportion of interfloor traffic correlates with the categories, i.e., low amount of interfloor traffic during lunch-peak implies low interfloor traffic during downpeak. Average downpeak traffic mix across all cases resembles Siikonen multi-tenant office down peak components, 20% incoming, 60% outgoing and 20% interfloor traffic [3].

5 DISCUSSION

Peak traffic patterns varied a lot between the studied buildings or rises. Generally, the highest peak demands and proportions of interfloor traffic occur during lunch time while morning uppeak and evening downpeak seem similar in both respects on average. The buildings were categorised based on the proportion of interfloor traffic during lunch-peak, which allowed to differentiate typical peak traffic patterns.

Average five-minute peak demand in the morning varied around 11% of population per five minutes depending on the interfloor category while the upper bound of 95% confidence interval varied around 12% per five minutes. Thus, the well-known required handling capacity of 12% per five minutes for uppeak seems a good value for standard designs [5,6,7]. In the studied buildings, the proportion of incoming traffic in the morning was surprisingly low compared to uppeak traffic mixes assumed in the design standards. While pure uppeak with 100% of incoming traffic is useful for determining handling capacity as a historical reference, a traffic mix of 85% incoming, 10% outgoing and 5% interfloor traffic has been used as an alternative [5,6,7]. To accommodate higher proportions of outgoing and interfloor traffic as found in this study, design simulations could be conducted with a traffic mix consisting of 70% incoming, 20% outgoing and 10% interfloor traffic.

During lunch time, average peak demands of around 13% per five minutes were observed. The averages are at the higher end of the current requirements for standard designs, which vary from 11%

to 13% per five minutes [5,6,7]. However, both the upper bounds of 95% confidence intervals and maximums clearly exceed these requirements. Hence, required handling capacity for lunch traffic could be increased, e.g., to 14-15% per five minutes especially in Southeast Asia. In the buildings in the low and the medium interfloor category, average lunch traffic mixes were close to the ones currently used in design simulations. However, the buildings with an attraction or transfer floor among the populated floors demonstrate the need for an alternative lunch traffic mix to be simulated: 30% incoming, 30% outgoing and 40% interfloor traffic. In some rare cases, the observed lunch traffic was pure two-way traffic without any interfloor traffic, which could be an option for simulations if local practices allow it.

Nowadays evening downpeak is not seen as a critical peak period for lift service as design standards do not set any requirements on it. Based on the measurements, peak demands in the evening follow peak demands in the morning on average. As lift groups are known to have a downpeak handling capacity of at least equal to uppeak handling capacity, the measurements do not indicate a need for adding the consideration of downpeak to design standards [3]. If desired, required handling capacity in downpeak could be defined 12% of population per five minutes, i.e., equal to the typical uppeak requirement, while traffic mix for design simulations could consist of 20% incoming, 60% outgoing and 20% interfloor traffic. Alternatively, pure downpeak with 100% outgoing traffic could be simulated to determine handling capacity in the cases where the whole building needs to be emptied at once.

In some of the measured buildings, peak demands remained well below handling capacities required by the design standards and, in some other buildings, greatly exceeded them during measurement days. Thus, variation seems to make peak demands unpredictable. The design standards should direct the selection of lift configurations into such that can handle peak demands in most of the buildings. However, exceptional cases, where peak demands exceed the required as well as the actual handling capacity, may occur. Therefore, handling capacities higher than required by the current standards could be considered, especially if local experience or building usage indicates very high demands during any of the peak periods. It is worth noticing that higher-than-standard handling capacities may not only target at satisfying peak demands but also at providing more spacious user experience and more robust service with respect to exceptional situations.

6 CONCLUSION

In this paper, new evidence on lift passenger demands was collected from 25 high-rise office buildings. To handle such a large amount of data, an algorithm analysing people flow data derived from automated passenger counts was developed to recognize typical peak periods known to occur in office buildings. Then, peak traffic patterns in the measured offices were studied statistically. The results indicate that the current requirements in design standards match quite well with the observed peak demands and traffic mixes.

However, some modifications or additions to the design standards could be considered. Required handling capacity for lunch traffic may need to be increased especially for Asian countries, where extremely high peak demands were observed in some cases. In addition, traffic mixes with higher proportions of interfloor traffic could be simulated for both uppeak and lunch traffic.

Due to high variation, people flow in each building appears rather unique reflecting the habits of the country and/or the tenant. To find stronger evidence on trends between different geographical areas or office types, a larger data set would be needed.

Peak demands in this study are scaled to the observed population of daily lift users including also absenteeism and visitors. Hence, research on actual occupancy rates would be needed to refine the estimation of design population. Knowledge of occupancy rates have become ever more important since the COVID-19 pandemic, which may have permanently influenced occupancy rates.

REFERENCES

[1] G.R. Strakosch, *Vertical Transportation: Elevators and Escalators, 2nd Edition*. John Wiley, New York (1983).

[2] R. Peters, R. Smith, and E. Evans, "The appraisal of lift passenger demand in modern office buildings". *Building Services Engineering Research and Technology*, Vol. 32, No. 2, 159-170 (2011).

[3] M-L. Siikonen, "Planning and control models for elevators in high-rise buildings". *Ph.D. thesis*, Helsinki University of Technology, Systems Analysis Laboratory (1997).

[4] D. Batey, and M. Kontturi, "Traffic analysis for high rise buildings to be modernized". *Elevator Technology 21 – Proceedings of Elevcon 2016*, IAAE, 26-35 (2016).

[5] ISO, *ISO 8100-32:2020 – Lifts for the transportation of persons and goods – Part 32: Planning and selection of passenger lifts to be installed in office, hotel and residential buildings*. International Organization for Standardization, Switzerland (2020).

[6] BCO, *BCO Guide to Specification 2019*. British Council for Offices, UK (2019).

[7] PCA, *A Guide to Office Building Quality: Third Edition*. The Property Council of Australia, Australia (2019).

[8] L.A. Zadeh, "The concept of a linguistic variable and its application to approximate reasoning - I". *Information Sciences*, Vol. 8, No. 3, 199-249 (1975).

BIOGRAPHICAL DETAILS

Janne Sorsa, D.Sc. (Tech.) in operations research, heads the People Flow Planning team for KONE Major Projects and has played a key role in establishing and further developing the KONE network of People Flow Planning experts. He joined KONE in 2001 to develop dispatching algorithms for double-deck lifts and has successfully improved the performance of KONE double-deck destination control. He has published over 30 articles on people flow planning, optimization, and simulation. Sorsa also acts as the convenor of ISO/TC 178/WG 6/SG 5 and the project lead for the ISO 8100-32 standard on planning and selection of passenger lifts. Additionally, he actively participates in the work of ISO/TC 178/WG 6/SG 4 on writing the requirements for lifts used to assist in building evacuation.

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