Computer Simulation of a Global Benchmarking Parameter for Real-time Monitoring of Lift Systems Energy Efficiency

Albert So*, Ricky Chan and Stefan Kaczmarczyk
Faculty of Arts, Science and Technology, The University of Northampton, United Kingdom
*Corresponding author's email address: alberttpso@gmail.com,

Keywords: Energy consumption, benchmarking parameter, lift traffic, lift drive, normalization, computersimulation

Abstract. At present, there are benchmarking procedures to assess the energy performance of lifts, e.g. VDI (4707-1/2) adopted in Germany as a pioneer, then replaced by ISO (BS EN ISO 25745-1:2012 and 25745-2:2015) in Europe, and the other in Hong Kong adopted by The Hong Kong Special Administrative Region (HKSAR) Government. The Hong Kong procedure focuses on the design performance of lift drives. The ISO standard further estimates the annual energy. To facilitate real time monitoring of energy performance of lift systems, a holistic normalization method (So et al 2005, Lam et al 2006) was developed more than ten years ago, which can simultaneously assess both drive efficiency and traffic control performance on a real-time basis, termed <J/kg-m> which is the name of the parameter measured in unit, J/kgm, and is now adopted by the HKSAR Government as a good practice in the *Technical Guidelines* of the *Energy Code*, but not yet enforced in the mandatory code. Values, not just the procedures, for benchmarking are demanded. In this article, such a parameter is evaluated under different drives and lift traffic control scenarios by using computer simulations, with the aim of arriving at a reasonable figure for benchmarking an energy efficient lift system with both an efficient drive as well as an efficient supervisory traffic control. This parameter could also be used to compare the performance of different types of intelligent car dispatchers. The simulation suggested a value of 50 J/kgm as acceptable while 40 J/kgm as good.

1 INTRODUCTION

The energy consumption of lift systems, in the past, did not receive much attention because it only accounts for a relatively small percentage of total energy consumption of a building. In fact, this statement is correct only when a commercial office building is considered, but not necessarily for residential buildings. According to the statistics of a government department in Hong Kong overseeing energy efficiency, the total energy consumption of the lift system in a typical office building is less than 11% of the energy consumption of the whole building (Yeung and Lau 2011). According to Asvestopoulos et al (2010), in Europe, the energy consumption of lifts typically represents 3% to 8% of the total energy consumption of buildings, depending on the structure and usage of the building, the type and number of lifts. They estimated that there were around 8.5 million lifts in operation worldwide. Now, this figure should be close to eleven to twelve millions, with an estimated growth of around 670,000 per year.

Schroeder (1986) developed a generalized formula to calculate the annual energy consumption of lifts per square metre of building space. Doolaard (1992) compared the relative consumption of energy by hydraulic lifts, AC-2 lifts, and ACVVVF lifts. Al-Sharif (1996) discussed several topics related to the energy consumption of lift systems by comparing the consumption of various types of drives and outlining the concept of regenerating power back into the supply grid. Lorente-Lafuente et al. (2013) studied the proportion of time taken in each of the three modes of operation of a lift, i.e. running, idle and standby, and hence the energy consumed by means of simulation tools, based on a set of buildings with different number of floors, different rated capacities of lifts, different rated speeds and different traffic modes, i.e. up-peak, down-peak, interfloor, and lunch peak under collective traffic control. Various publications on energy models and simulation of lifts are also available (Al-Sharif et al. 2004, Adak et al. 2013).

In this paper, a quick review of various existing energy codes are first made, followed by the introduction of the holistic or global energy efficiency benchmarking parameter that can be measured real-time and may cover different types of drives, including but not limited to AC2, ACVV, DCWL, DCTL, ACVVVF (scalar and vectored), PMSM, linear machines, hydraulic etc. and dispatchers.

2 SELECTED EXISTING ENERGY CODES

2.1 The Energy Code in Europe

The first energy guideline for lifts and escalators in Europe may refer to VDI 4707 initiated in Germany with guidelines published by the Association of German Engineers (VDI), a draft of which appeared in the end of 2007. It was later replaced by BS EN ISO 25745-1:2012 and BS EN ISO 25745-2:2015 which are now used in almost every country in Europe. According to Lorente-Lafuente et al. (2013a, 2014) ISO 25745-2 specifies a method to estimate energy consumption based on measured values, calculation, or simulation, on an annual basis for traction, hydraulic and positive drive lifts on a single unit basis, and an energy classification system for new, existing and modernized units. The energy data tables in ISO 25745 were derived from thousands of computer simulations considering lift trips, kinematics, energy figures and building usages while the lift dependent data was obtained from modelling and calculation. The accuracy of energy estimation depends on both the motor design and the dispatching algorithms (Siikonen et al. 2010, Siikonen 2012, Lorente-Lafuente 2013b). Expected trips per day, load factor, operating hours of running, standby and idle modes, and average travelling distance of a lift are also considered. Then, the annual consumption is estimated by ample simulations and statistics arriving at energy models of different types of lifts and controllers, matched to usage categories.

2.2 The Building Energy Code of Hong Kong

The first code of practice related to energy in Hong Kong is perhaps the *Code of Practice for Overall Thermal Transfer Value (OTTV) in Buildings* (Buildings 1995) published by the Hong Kong Government in April, 1995. Then, in 1997, a task force with four sub-committees was established within the Electrical & Mechanical Services Department (EMSD) of the HKSAR Government to draft codes of a similar nature but on different building systems, namely Lighting, Air-Conditioning, Electrical Services and Lifts and Escalators between 1997 and 1999. From 1999 to 2011, these codes had been implemented on a voluntary basis while building owners had full freedom to follow or not. In 2012, the four codes, and others, were combined into one document, *Code of Practice for Energy Efficiency of Building Services Installation*, called *Building Energy Code* or BEC in short (EMSD 2012a). Under the enforcement of the *Building Energy Efficiency Ordinance* Cap 610 published in the same year, such combined code of practice became mandatory in Hong Kong. All new and extensively retrofitted buildings need to comply with such a code of practice. By 2015, the code was slightly revised with some tightened clauses and published (EMSD 2015a). As a companion to the code, a set of guidelines was also published by the EMSD in 2012, revised in 2015 (EMSD 2012b, EMSD 2015b). The next revision is expected to be published by late 2018.

Inside the BEC, tables giving maximum power consumption (in kW) of a motor drive of a lift as measured under a fully-loaded rated-speed upward movement are used to assess whether the drive performance passed or failed. There are separate tables for hydraulic lifts, escalators and passenger conveyors. According to the BEC, lift energy performance is mainly dependent on the drive performance while the supervisory control has no way to contribute.

3 THE BENCHMARKING PARAMETER, <J/kg-m>

The Hong Kong BEC concerns the instantaneous power consumption of the drive measured in kW, not accumulated energy measured in Joules, during a fully-loaded rated-speed up journey. Under some circumstances, regenerative braking is mandatory but this has no effect on the tables stipulating the maximum instantaneous power consumption.

The first author of this paper, together with other researchers, noticed twelve years ago (So et al 2005) that merely an energy efficient motor drive is not the ultimate determining factor of an energy efficient lift system. Efficiency of the drive can only account for the hardware performance, whereas another main saving should come from the supervisory traffic control. In that 2005 paper (So et al 2005), it was shown that by using the same motor drive, a significant reduction in energy consumption could be obtained by using different traffic controllers. One with artificial intelligence associated with energy saving could achieve a distinctive result. Based on this argument, a good benchmarking parameter for energy comparison of lift systems must take care of both the hard physical motor drive performance as well as the soft traffic control algorithms. Therefore, the idea of <J/kg-m>, with a unit J/kgm, was suggested. However, the code authorities in Hong Kong asked for exact values for benchmarking, not just concept and algorithm. The goal of this article is to present the procedures to find out a reasonable value of this benchmarking parameter for different types of drives and dispatchers by simulation.

The basic concept of <J/kg-m> is simple. It is the average energy to convey one unit of mass, either passengers or goods, to travel a distance of one metre, irrespective of direction or speed over a fixed and agreed period of time. In simple physics, it is an overall term of efficiency, "J" representing the input (energy) to the lift system and "kg-m" representing the output (how many passengers can be handled and how far they can go) of the lift system. Obviously, <J/kg-m> should be as low as possible. There are two ways to lower its value. An energy efficient motor drive can of course lower such average value by reducing the numerator of the ratio, while an energy efficient traffic control system can lower such average value by increasing the denominator of the ratio. The latter is achieved by handling more passengers in one trip. In other words, by using <J/kg-m>, it is worth to use more energy to convey more passengers in one round trip. This is in particular more significant to energy efficiency when the lift is not fully loaded.

To evaluate this benchmarking value on a real time basis, four measurements have to be made instantaneously and continuously during daily operation:

i) energy consumed, in Joules, over the fixed period of time, *T*, say 7,200 seconds = 2 hours long; ii) mass of load, in kilograms, inside the car, at any time within *T*;

iii) position of car, in metres, along the hoist-way at any time within *T*; this is to estimate the distance traveled by the car; and

iv) the status of the brake because a brake-to-brake journey is always considered for the denominator.

This period of *T* seconds long is called a measurement window and this window is moving along the time axis. This parameter has been included as Section 8.8 in the guidelines of the *BEC* published in 2012 (EMSD 2012b) and in 2015 (EMSD 2015b) as a good practice recommended to lift owners, manufacturers and maintenance contractors. However, although (i) could be easily measured by an external power meter (actually mandatory in Section 8.7.1 of the 2015 *BEC*) using the well known Two-Wattmeter Method, the quantities (ii), (iii) and (iv) are usually not readily available to the lift owner or user. Thanks to the publication of the recently approved BACnet objects (ASHRAE 2016) for lifts and escalators, all four can be obtained either directly or indirectly by the appropriate implementation of the relevant BACnet objects, namely "Energy Meter", "Car_Position", "Car_Load", "Car_Door_Status", and "Landing_Door_Status" respectively, in Table 12-Y. Car Load is only considered by the parameter when both landing and car doors are closed and the car is moving.

Within the period of time from 0 s to T s, say two hours, i.e. 2 × 3600 s = 7200 s, there could be N number of brake-to-brake journeys of one car or several cars belonging to the same bank. The ith brake-to-brake journey commences at the instant when the brake is released at the departing floor for the car to accelerate and ends at the instant when the brake is applied again for the car to stop at the destination floor. During this journey, w_i kg of load is conveyed and a total distance, d_i m, is displaced, where i runs from 1 to N.

Without loss of generality, this definition also applies to a bank of lift cars. A time increment, ΔT, say 15 minutes can be defined so that another time period from ΔT to $T+\Delta T$ can be formulated. The same process is conducted within this new time period, and is being repeated, thus the provision of moving windows. At the same time, the total energy, $E_T(k)$, consumed during a particular period, the kth period, of T s has to be recorded. It is obvious that $E_T(k)$ includes not just the consumption of the motor drive but others including lighting, ventilation, control and indication etc. Eventually, one <J/kg-m> (k) value can be found for the k th time period, either for one car or a bank of cars. A daily or weekly average can finally be obtained. So, for the k th time period, the following equation (1) is valid. Any brake-to-brake journey across the two borders of the k th period could also be included in equation (1) as it does not affect the statistics by much.

$$\langle \text{J/kg-m} \rangle (k) = \frac{E_T(k)}{\sum_{i=1}^{N} w_i(k) d_i(k)} \qquad (1)$$

Such a parameter was also employed to develop a statistically energy saving scheme by varying the counterweight setting of a lift from time to time, say every two weeks when the lift is serviced (So et al 2012). In the 2012 and 2015 *BEC* Guidelines, it was stated that typical values of the parameter, <J/kgm>, could vary between 30 J/kgm and 150 J/kgm while in the 2005 article (So et al 2005), a value of 50 J/kgm was considered acceptable.

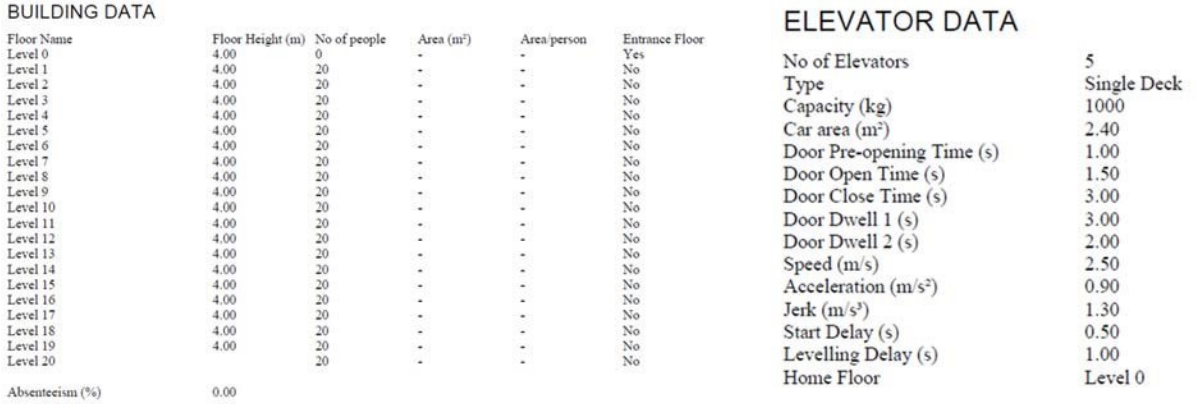
4 STUDY OF THE BENCHMARKING PARAMETER BY SIMULATION

4.1 The Simulation Platform

At this moment, the parameter <J/kg-m> is not evaluated by any commercial simulation software on the market. So, the procedure discussed in this article is to simulate a group of lift cars to serve different types of passenger demands to make available landing and car calls, and a spatial plot of such simulation. Then, energy models of different drives are implemented on the plot to find out the three parameters (i), (ii) and (iii) in Section 3 of this article and finally <J/kg-m> can be evaluated. For on-site assessment, no energy model is required because the accumulated energy consumed over a period, *T*, can be measured directly. A widely established simulation tool on the market, Elevate^{TM} 8, has been used to arrive at the spatial plot. Under "report options", "spatial plot" was selected and a graphical output was shown in the results. The table form of "spatial plot" can be obtained by selecting the Excel output on the tool bar.

It is obvious that a lower <J/kg-m> can be obtained if a more energy efficient motor drive is employed provided all other factors are identical. The scope of this article is to compare its values between different supervisory control systems as well while regenerative braking is also included for completeness. Therefore, more or less the same motor drive and the same passenger demand profile were used for a 4.5 hour simulation exercise, from 7:45 am to 12:15 am, including three types of traffic, up-peak, interfloor and down-peak. For a fair comparison, a bank of 4 lifts, each of capacity 1,000 kg and a rated speed of 2.5 m/s, was employed to serve a building of 20 floors tall, not including the ground floor terminal. In one simulation case, 5 lifts were used to demonstrate the difference when the system was over-designed. Each floor had a constant height of 4 m typically and population density was uniformly 20 people per floor. Each passenger had an average weight of 75 kg and therefore a fully loaded car could at most accommodate 13 passengers. Door times were 1 s (pre-open), 1.5 s (open) and 3 s (close).
Acceleration/deceleration rate was fixed at 0.9 m/s^2 and the jerk was fixed at 1.3 m/s^3. Car door dwell time was fixed at 2 s while landing call dwell time was fixed at 3 s. There were a start delay of 0.5 s and a levelling delay of 1 s. Usually, all the 20 floors were served by these 4-5 cars. But in a couple of scenarios, zoning was employed to improve traffic performance.

During morning up-peak from 7:45 am to 10 am, there was a constant arrival rate of 60 passengers per 5 minute interval, i.e. 15%, while their destination probability to every floor was 5%. During the interfloor period from 10 am to 11 am, the arrival rate at the ground floor is 5 passengers per 5 minute interval (1.25%) and that at each floor is 2 passengers per 5 minute interval (10%). Their destination probability to any floor except itself, including the ground floor, is uniformly 5%. During before noon down-peak from 11 am to 12:15 pm, the arrival rate at the ground floor was 0 passenger / 5 minute interval and at every floor were 4 passengers / 5 minute interval (20%) with a 100% destination probability to the ground floor main terminal.



BUILDING DATA

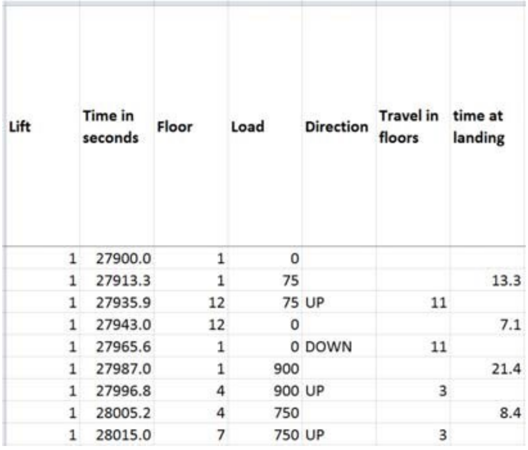
Floor Name	Floor Height (m)	No of people	Area (m²)	Area/person	Entrance Floor
Level 0	4.00	0	-	-	Yes
Level 1	4.00	20	-	-	No
Level 2	4.00	20	-	-	No
Level 3	4.00	20	-	-	No
Level 4	4.00	20	-	-	No
Level 5	4.00	20	-	-	No
Level 6	4.00	20	-	-	No
Level 7	4.00	20	-	-	No
Level 8	4.00	20	-	-	No
Level 9	4.00	20	-	-	No
Level 10	4.00	20	-	-	No
Level 11	4.00	20	-	-	No
Level 12	4.00	20	-	-	No
Level 13	4.00	20	-	-	No
Level 14	4.00	20	-	-	No
Level 15	4.00	20	-	-	No
Level 16	4.00	20	-	-	No
Level 17	4.00	20	-	-	No
Level 18	4.00	20	-	-	No
Level 19	4.00	20	-	-	No
Level 20		20	-	-	No
Absenteeism (%)	0.00				

ELEVATOR DATA

No of Elevators	5
Type	Single Deck
Capacity (kg)	1000
Car area (m²)	2.40
Door Pre-opening Time (s)	1.00
Door Open Time (s)	1.50
Door Close Time (s)	3.00
Door Dwell 1 (s)	3.00
Door Dwell 2 (s)	2.00
Speed (m/s)	2.50
Acceleration (m/s²)	0.90
Jerk (m/s³)	1.30
Start Delay (s)	0.50
Levelling Delay (s)	1.00
Home Floor	Level 0

[redacted]

Figure 1 shows the building and lift data. After each simulation of the 4.5 hours, a spatial plot, in table form, actually a list of time based activities of the lifts, which is Excel compatible, was produced as shown in Figure 2. Every row in the spatial plot indicates the status of the lift car at a given time instant. The first column is the lift number which normally runs from 1 to 4 in our study and in one additional case, 5. The second column shows the absolute time of the event, say a value of 27900 s in Excel being equivalent to a converted time of “7:45:00”. The third column shows the instantaneous position of the lift car on a floor by floor basis, the fourth column showing the exact weight of passengers (converted to number of passengers by dividing the weight by 75 kg) inside the lift car. The fifth column shows the direction of travel, either “Up” or “Down” while a space means the car stops at a particular floor. The sixth column shows the number of floors travelled by the car either in the “Up” or “Down” direction. Of course, no floor has been travelled when the direction is a space. When the car stops, the last column shows how long in seconds it has stopped there.



Lift	Time in seconds	Floor	Load	Direction	Travel in floors	time at landing
1	27900.0	1	0			
1	27913.3	1	75			13.3
1	27935.9	12	75	UP	11	
1	27943.0	12	0			7.1
1	27965.6	1	0	DOWN	11	
1	27987.0	1	900			21.4
1	27996.8	4	900	UP	3	
1	28005.2	4	750			8.4
1	28015.0	7	750	UP	3	

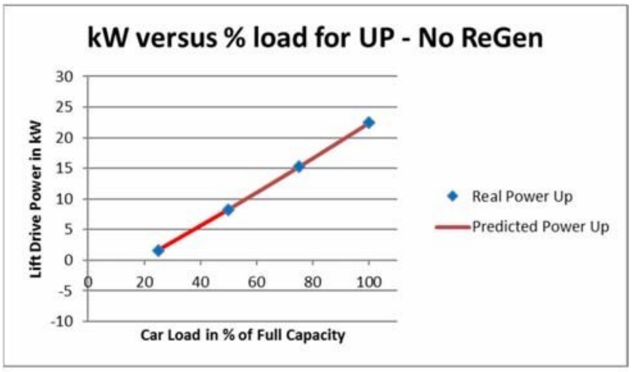
[redacted]

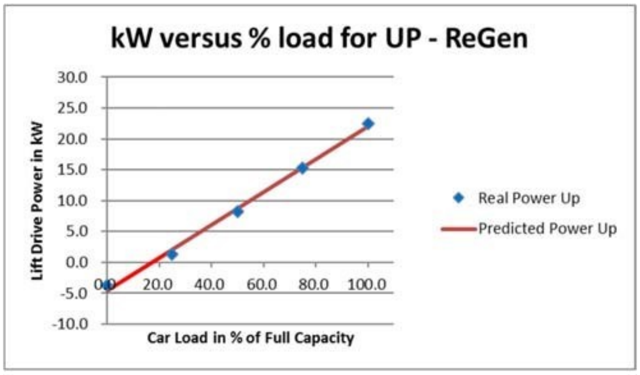
Energy consumed was calculated in two parts. The first part was the energy of movement which depends on the load, direction of travel and the number of floors travelled. The second part was idle energy which depends on the duration when the car stops at a particular floor. By manipulating column 3 and column 4, the total “kg-m” within the measurement window, *T*, could be calculated. A brake-to-brake journey spans across two rows on column 5 from one blank space to the next blank space. Then, energy calculation was based on an energy model of different drives and configurations. Such an energy model was applied to a brake-to-brake journey once the in-car load and its direction of travel were known while the total energy consumed was equal to the average power multiplied by the time spent of that journey.

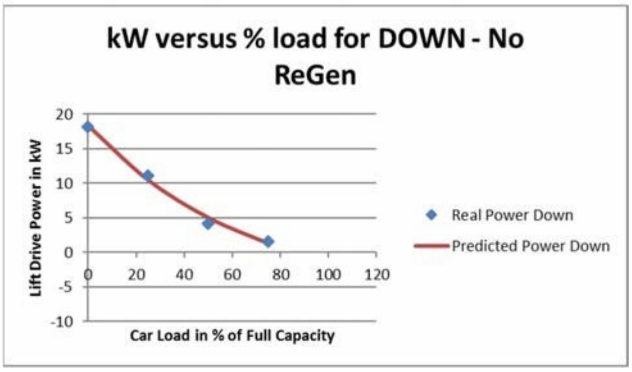
4.2 Energy Models

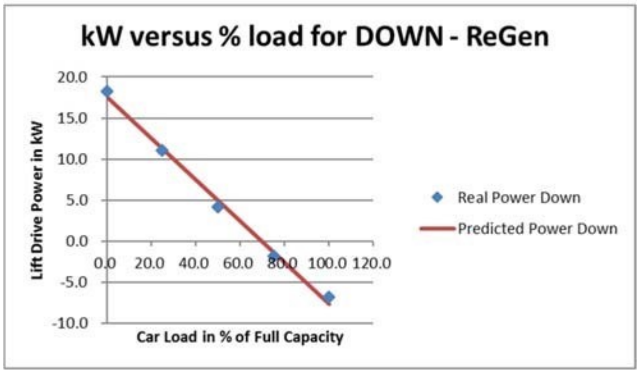
Throughout the simulation, three types of drives were considered, namely the modern standard VVVF (variable speed variable frequency) drive without regenerative braking, the standard VVVF drive with regenerative braking, and the less modern MG (motor generator set) drive. The models are all available on the simulation platform under a discrete mode, i.e., power consumption in kW when the car is 0%, 25%, 50%, 75% and 100% loaded and travels upward or downward. A constant value throughout the journey was assumed while variations during acceleration, deceleration and leveling were neglected.
Curve fitting was employed in our exercise with one energy equation derived for each of the three types of drive, under idle, up and down movements.

Figure 3(a) shows the power curves of the standard VVVF drive without re-generative braking, up and down respectively. The idle consumption is constant at 1.6 kW. Since the re-generative power during full loaded down or no loaded up etc. is dissipated in the resistor above the control cabinet, power consumption is set to 1.6 kW constant when the load is below 25% (up) or above 75% (down). Figure 3(b) shows the power curves of the same VVVF drive but with re-generative braking. Again, the idle consumption is constantly at 1.6 kW. Figure 3(c) shows the power curves of a more conventional M-G (motor generator) set drive with an idle power of 3.6 kW. Equation set (2) shows the equations obtained after curve fitting, that could give a continuous estimation of power consumption under all load between 0% to 100%. The continuous curves in Figures 3(a) to 3(c) show the performance of the equations after curve fitting while the five dots show the raw data from the simulation platform. Here, *P* is the estimated power consumption in kW and *L* is the in-car load in percentage of rated capacity.



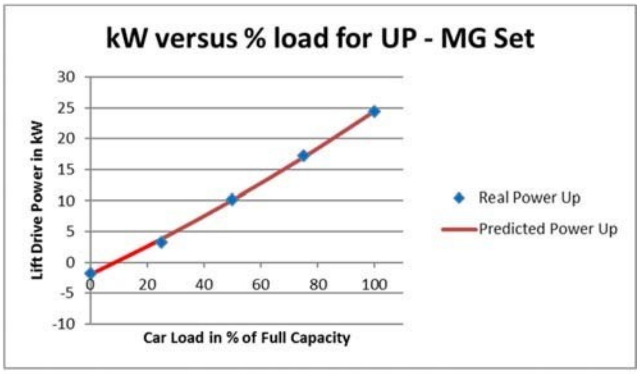


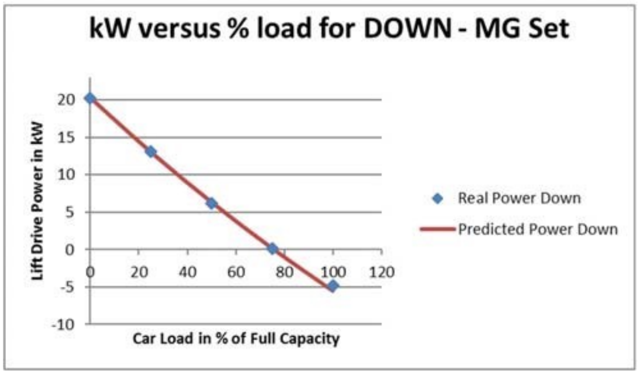




[redacted]

[redacted]





[redacted]

For ACVVVF drive without re-generative braking:

Up - $P \square -165.567509705713 \square 160.730684113428 e^{0.00156730376735839L}$ kW Down
- $P \square -7.09935520239914 \square 25.4624088666429 e^{-0.0148552950302361L}$ kW

For ACVVVF drive with re-generative braking:

Up - $P \square 0.265599861984985L \square 4.60000336963263$ kW
Down - $P \square -0.251599913906517L \square 17.5599933949248$ kW (2)

For M -G set drive:

Up - $P \square -65.068223297976 \square 63.0409991840916 e^{0.00351762064223245L}$ kW
Down - $P \square -72.2839916033987 \square 92.5176475710003 e^{-0.0032609325869072L}$ kW

It should be noted that this energy model only accounts for the motor consumption, where others like lighting, ventilation etc. are not included. Having said that, if no air-conditioner is installed on the car top, the overall extra consumption is just less than 100 W, negligible as compared with the kW or tens of kW consumed by the motor drive.

4.3 Scenarios of Simulation

The simulation was on the same passenger demand profile and the same lift configuration, by using different control algorithms, namely GC (group collective control) without zoning, group collective control with zoning, ETA (estimated time of arrival) and ACA (adaptive call allocation). A good reference to all these would be the book by Barney and Al-Sharif (Barney et al 2016) and the discussion below is based on this book.

One of the most conventional car dispatchers for a bank of lifts may be termed “group collective control”. All landing and car calls are made by pressing pushbuttons by the passengers and they are handled in strict floor sequence. The lift automatically stops at landings for which calls have been registered, following the floor sequence. There are usually three types, namely non-directional, down-directional and full collective. Here, in the simulation, “full collective control” is used where passengers are expected to behave by pushing either the up or down landing call buttons and also the car call buttons inside the car correctly. Additional “up-peak” and “down-peak” algorithms are also implemented in the simulation platform.

Usually, a lift car serves all floors of the building. Since the probability of any passenger to any floor is constant in this simulation, the number of stops could be reduced by using zoning, and thus the round trip time can be shortened and finally the handling capacity can be increased. In the simulation, two zones were allocated, low rise from 1/F to 9/F and high rise from 10/F to 20/F. Car 1 served all 20 floors; car 2 and car 3 served the high-rise zone only; car 4 served the low-rise zone.

According to Barney et al. (2016, see section 11.2), by 1973, a computer based control system was implemented where the landing calls were assigned to lift cars according to the time each car was estimated to take to answer the call. Such algorithm was termed ETA (estimated time of arrival) where instantaneous registered car and landing calls, position, direction of travel and status of each lift were continuously scanned. A newly registered landing call was allocated to the lifts committed to move towards the call in the same direction as the call, and also for any uncommitted lifts.

There are different names of ACA (adaptive call allocation) pointing to similar control algorithms, namely call allocation, hall call allocation, destination call allocation and of course ACA. With its implementation, car calls are no longer made inside the car. Car calls and landing calls are made on the same panel at the landing in one go. The passenger is required to inform the system not just the direction of intended travel but the exact destination floor number. The system returns with the exact car that this passenger must take, not any other. This system has been proven for increased handling capacity but sometimes with a penalty of increased waiting time. But the transit time could be shorter because each car tends to take more passengers going to the same destination floor and hence less stops throughout a round trip.

5 RESULTS

Overall, ten scenarios were simulated over the same passenger demand profile for a duration of 4.5 hours, from 7:45 am to 12:15 pm. Each scenario was done independently using the same passenger profile. In other words, the spatial plots of all ten scenarios were different. The goal of this exercise was to investigate how the benchmarking parameter, <J/kg-m>, varied under different scenarios so that a reasonably standard value could be proposed for mandatory implementation in the future.

The duration of the measurement window, T, was set to 2 hours and the moving increment was set to $\mathrm{D}T =$ 15 minutes. The first 15 and last 15 minutes were ignored due to instability. Hence, nine moving windows were obtained, centered at 9 am, (period $k = 1$), 9:15 am (period $k = 2$), 9:30 am (period $k = 3$), 9:45 am (period $k = 4$), 10 am (period $k = 5$), 10:15 am (period $k = 6$), 10:30 am (period $k = 7$), 10:45 am (period $k = 8$), and 11 am (period $k = 9$). Actually, a window centered at 9 am represented the window from 8 am to 10 am, and similar for others. It was possible to see the changes in <J/kg-m> when the passenger demand changed from up-peak, to interfloor and finally to down-peak.

Tables 1.1 to 1.6 show the results of <J/kg-m> of the nine periods of windows under ten scenarios. The <J/kg-m> of individual car and that of a combination of the whole bank of 4 or 5 cars of each is tabulated in five columns while the last column shows the average <J/kg-m> of the whole system over 4.5 hours of simulation. Such average value is the un-weighted average of all cars of the nine periods of windows. During real operation, if the system is monitored 24/7, a weighted average value may be more reasonable because values of those 2-hour windows after 6 pm and before 7 am during working days and throughout the whole day of weekends and holidays of, say an office building, are misleading due to the exceptionally low traffic flow while some energy is continuously consumed. The number in bracket under the average <J/kg-m> of the whole system indicates the rank of each scenario, "1" being the best and "10" being the worst in these tens cases of simulation.

The <J/kg-m> value of all cars is not an arithmetic average of the value of each of the four cars, j = 1 to 4. It is given by equation set (3). However, the value in the final column is the real arithmetic average of all nine values for the nine periods.

$$\langle \text{J/kg}-\text{m} \rangle \text{ (all cars) } (k) = \frac{\sum_{j=1}^{4} E_{Tj}(k)}{\sum_{j=1}^{4} \sum_{i=1}^{N(k)} w_{ji}(k) d_{ji}(k)} \qquad (3)$$

$$\langle \text{J/kg -m} \rangle \text{ (average over all periods) } = \frac{\sum_{k=1}^{9} \langle \text{J/kg -m} \rangle \text{ (all cars) } (k)}{9}$$

Here, $E_{Tj}(k)$ is the total energy consumption of the j th car within the kth period; $w_{ji}(k)$ is the in-car load of the j th car during the i th brake-to-brake journey within the k th period; $d_{ji}(k)$ is the distance traveled, irrespective of direction, of the j th car during the i th brake-to-brake journey within the k th period. Equation set (3) is the general equation and j = 1 (to) n, where n = 4 or 5 in our simulation.

Table 1.1 Raw Results of <J/kg-m> based on Computer Simulations of 4-5 Cars over 9 Periods

Scenario	Period	Car 1	Car 2	Car 3	Car 4	All Cars	All Cars average over 9 periods (rank)
Group Collective – Auto without zoning and VVVF drive without regenerative braking	1	46.6	46.4	45.5	44.4	45.8	46.0 (9)
	2	46.9	48.6	47.4	46.8	47.4	
	3	50.3	51.3	47.6	47.7	49.2	
	4	50.5	53.9	48.8	49.3	50.5	
	5	53.6	57.3	48.8	50.5	52.4	
	6	49.4	51.8	46.5	45.7	48.3	
	7	47.5	45.7	39.3	41.0	43.1	
	8	39.4	39.1	36.5	39.5	38.6	
	9	36.1	35.0	29.9	34.1	33.7	
Group Collective – Auto without zoning and VVVF drive with regenerative braking	1	44.2	43.9	43.2	42.5	43.5	40.4 (5)
	2	44.2	46.1	44.6	44.3	44.8	
	3	46.8	48.0	44.3	45.0	46.0	
	4	46.4	49.7	44.7	45.9	46.6	
	5	48.6	52.6	44.3	46.5	47.9	

	6	43.5	46.4	41.0	40.3	42.7	
	7	40.2	39.3	32.9	34.3	36.5	
	8	31.1	31.9	28.7	31.4	30.8	
	9	26.6	27.1	21.7	25.0	25.0	

Table 1.2 Raw Results of <J/kg-m> based on Computer Simulations of 4-5 Cars over 9 Periods

Scenario	Period	Car 1	Car 2	Car 3	Car 4	All Cars	All Cars average over 9 periods (rank)
Group Collective – Auto without zoning and MG Set drive	1	53.1	53.1	52.4	50.7	52.3	51.5 (10)
	2	53.5	56.0	54.4	53.3	54.3	
	3	57.2	59.1	54.7	54.3	56.2	
	4	57.5	61.7	56.2	55.9	57.7	
	5	60.8	65.9	56.2	57.4	59.9	
	6	55.9	59.4	53.3	51.5	54.9	
	7	53.1	51.7	44.3	45.7	48.5	
	8	43.4	43.4	40.6	43.4	42.7	
	9	39.2	38.9	32.5	36.7	36.7	

Table 1.3 Raw Results of <J/kg-m> based on Computer Simulations of 4-5 Cars over 9 Periods

Scenario	Period	Car 1	Car 2	Car 3	Car 4	All Cars	All Cars average over 9 periods (rank)
Group Collective – Auto with zoning and VVVF drive without regenerative braking	1	50.8	38.9	38.3	42.9	42.1	42.8 (7)
	2	51.5	42.4	39.6	44.8	44.1	
	3	54.5	42.4	41.7	47.5	45.9	
	4	55.1	44.3	44.3	50.7	48.1	
	5	57.0	46.3	45.5	53.5	50.1	
	6	50.0	41.3	43.6	52.5	46.5	
	7	43.4	34.7	37.9	49.7	40.7	
	8	38.1	31.5	31.2	48.2	36.2	
	9	29.9	26.1	28.7	48.0	31.3	
Group Collective – Auto with zoning and VVVF drive with regenerative braking	1	45.4	38.9	33.8	36.7	38.1	35.7 (1)
	2	47.0	40.1	35.1	38.5	39.5	
	3	49.2	41.6	35.1	39.7	40.5	
	4	47.7	43.2	37.4	39.0	41.3	
	5	48.7	45.5	39.6	38.8	42.8	
	6	39.4	43.2	35.0	33.8	37.7	

	7	28.2	39.4	30.9	30.2	32.0	
	8	20.7	32.9	30.9	26.4	27.3	
	9	14.8	29.1	28.9	19.2	21.9	

Table 1.4 Raw Results of <J/kg-m> based on Computer Simulations of 4-5 Cars over 9 Periods

Scenario	Period	Car 1	Car 2	Car 3	Car 4	All Cars	All Cars average over 9 periods (rank)
ETA – without zoning, and VVVF drive without regenerative braking	1	43.7	42.6	44.1	43.1	43.4	42.7 (6)
	2	45.4	44.7	45.2	44.1	44.8	
	3	46.9	46.3	44.3	45.9	45.8	
	4	48.6	47.9	45.1	46.6	47.0	
	5	52.5	49.2	47.4	48.1	49.2	
	6	49.0	43.9	46.6	43.6	45.7	
	7	42.8	37.3	42.9	39.0	40.4	
	8	40.0	35.7	37.1	33.9	36.6	
	9	36.0	30.1	32.5	29.1	31.8	
ETA –without zoning, and VVVF drive with regenerative braking	1	40.8	40.0	41.0	40.4	40.5	37.2 (2)
	2	42.1	41.5	41.9	40.8	41.6	

	3	43.1	42.4	40.9	42.1	42.1	
	4	43.8	43.2	41.0	42.2	42.5	
	5	47.2	44.1	42.8	43.2	44.3	
	6	42.2	37.8	40.5	37.4	39.4	
	7	35.3	30.6	36.0	31.8	33.3	
	8	31.2	27.5	29.4	26.1	28.5	
	9	26.3	21.3	24.0	20.6	22.9	

Table 1.5 Raw Results of <J/kg-m> based on Computer Simulations of 4-5 Cars over 9 Periods

Scenario	Period	Car 1	Car 2	Car 3	Car 4	All Cars	All Cars average over 9 periods (rank)
ACA – without zoning, and VVVF drive without regenerative braking	1	42.3	45.2	44.1	44.2	43.9	43.2 (8)
	2	44.4	47.6	45.0	44.4	45.3	
	3	47.9	51.5	46.3	46.2	47.9	
	4	49.9	52.4	47.6	48.9	49.6	
	5	53.0	51.9	48.7	50.1	50.8	
	6	47.6	45.3	45.6	44.1	45.6	
	7	41.9	38.8	39.6	37.0	39.3	

	8	37.5	35.8	35.6	32.5	35.3	
	9	32.7	31.0	30.3	29.0	30.7	
ACA – without zoning, and VVVF drive with regenerative braking	1	39.8	43.6	41.3	41.9	41.6	38.3 (3)
	2	40.9	45.2	43.3	42.5	42.9	
	3	43.4	46.6	43.8	41.9	43.9	
	4	44.9	47.9	46.0	41.8	45.1	
	5	45.4	48.6	46.8	44.2	46.2	
	6	40.0	43.6	38.9	40.6	40.7	
	7	33.1	35.8	32.8	34.0	33.9	
	8	26.5	29.3	26.8	28.8	27.8	
	9	21.3	24.3	21.9	24.0	22.8	

Table 1.6 Raw Results of <J/kg-m> based on Computer Simulations of 4-5 Cars over 9 Periods

Scenario	Period	Car 1	Car 2	Car 3	Car 4	Car 5	All Cars	All Cars average over 9 periods (rank)
ACA – without zoning, and VVVF drive with regenerative braking, 5 cars	1	41.0	40.7	35.8	45.5	60.7	42.7	39.4 (4)
	2	42.9	43.5	47.8	46.9	63.5	47.0	
	3	44.6	45.7	51.6	47.8	47.6	47.2	

4	47.5	47.1	53.0	51.1	51.5	49.8
5	50.8	48.5	54.7	54.1	53.0	52.0
6	46.2	44.7	50.8	50.4	43.0	46.7
7	42.3	40.2	46.2	44.9	37.1	41.8
8	36.1	34.7	41.1	37.6	31.5	35.9
9	33.5	31.7	35.5	32.4	27.5	31.9

For easy comparison, the ranking order is tabulated in Table 2 again.

Table 2 Ranking Order of Overall Average <J/kg-m> of Scenarios

Rank (actual <J/kg-m>, the lower the better)	Scenario
1 (35.7)	Group Collective – Auto with zoning and VVVF drive with regenerative braking
2 (37.2)	ETA –without zoning, and VVVF drive with regenerative braking
3 (38.3)	ACA – without zoning, and VVVF drive with regenerative braking
4 (39.4)	ACA – without zoning, and VVVF drive with regenerative braking, 5 cars
5 (40.4)	Group Collective – Auto without zoning and VVVF drive with regenerative braking
6 (42.7)	ETA – without zoning, and VVVF drive without regenerative braking
7 (42.8)	Group Collective – Auto with zoning and VVVF drive without regenerative braking
8 (43.2)	ACA – without zoning, and VVVF drive without regenerative braking
9 (46.0)	Group Collective – Auto without zoning and VVVF drive without regenerative braking
10 (51.5)	Group Collective – Auto without zoning and MG Set drive

There are several observations from Tables 1.1 to 1.6 and they are as follows.

a) <J/kg-m> tends to be higher during the transition between up-peak and interfloor traffic, and gets lower during down-peak traffic.
b) <J/kg-m> tends to be much lower for drives with re-generative braking facility even of the same traffic control, thus proving that re-generative braking is necessary for all modern energy efficient systems. That is obviously revealed by comparing ranks 5 and 9.
c) The values are between 35.7 and 51.5, which are rather stable to be confined within a narrow range, while they could be classified into three categories, four below 40.0, five between 40.0 and 50.0 and one above 50.0.
d) Zoning seems to give a better performance.
e) Computer based intelligent traffic control can give a better performance.
f) With reference to ranks 9 and 10, it is confirmed that MG set drive is not energy efficient while all modern drives tend to be more energy efficient.
g) With reference to ranks 3 and 4, it seems that overdesign (5 cars versus 4 cars) could give a slightly poorer performance because cars are not always fully loaded during peaks.
h) The suggestion of using 50 J/kgm as an acceptable reference value of <J/kg-m> in the 2005 article (So et al 2005) seems to be justified by this simulation exercise here because all modern drives could give a <J/kg-m> value below 50 J/kgm. Perhaps the next indicator point for a good reference value may be 40 J/kgm.

6 CONCLUSION

In sustainable development of the modern built environment, the energy efficiency of all building systems becomes a key consideration. Energy efficient lifts are of high demand and thus, international and national energy codes were prepared to improve their performance. So far, the emphasis has mainly been put on the physical aspect, i.e. the energy efficiency of the motor drive while the soft side of supervisory control may also contribute to energy performance. The parameter, <J/kgm>, was proposed more than ten years ago, and was believed to tackle both aspects of motor drive performance and traffic control performance on a real time basis. Its meaning is straight forward from a physics point of view, which resembles the COP (coefficient of performance) used in the HVAC industry. Ten years ago, it could be difficult to measure the <J/kg-m> on-site due to the unavailability of instantaneous data of car position and car load. Now, as the majority of lift systems in high-rise buildings are computerized, such information is readily available. With the cooperation of the lift manufacturers or the maintenance contractors, it should not be difficult to extract such information on a real-time basis through a local area network. The updated BACnet object list has already included all necessary objects to evaluate this parameter.

The theme of this article is to compare the performance of different traffic control systems based on the same passenger demand profile and a couple of standard motor drives. It has been found that the acceptable reference value of 50 J/kgm of <J/kg-m> proposed more than ten years ago seems to be still valid, and the result evaluated among the ten different scenarios indicates that the parameter is quite robust as the value is confined within a small range. The order of ranking as observed seems to be reasonable according to what the industry expects.

In order to provide a solid reference value for the whole industry, more measurement and simulations would be needed. But this article has provided the methodology to achieve part of the goal. At this moment, two reference threshold points of <J/kg-m> could perhaps be suggested, namely 50 J/kgm or below for an acceptable energy efficient system and 40 J/kgm or below for a good energy efficient system, the lower the better. The window of measurement could be fixed at 2 hours long while the moving interval at 15 minutes. The overall average value of a bank of lifts could be evaluated by taking the period from 7 am to 6 pm, five days a week for a high-rise office building.

During regular and busy hours, the usual situation in Hong Kong, when the traffic is normal to high, the standby power has already been included in the parameter <J/kg-m>. During low traffic period, the calculated value tends to rise as a lift spends more time in standby mode because the denominator may get smaller faster than that of the nominator. Under such circumstances, the lift system is still considered energy inefficient because one or more lifts must be switched off and placed in parking mode so that the denominator becomes smaller as well. From a systematic point of view, <J/kg-m> does not go up too much as one or more lifts are disabled. At mid-night when there is almost no traffic at all while at least one lift has to be operating but idle, <J/kg-m> may get to infinity as the denominator reaches zero. Two solutions are suggested here, one using J/s in place of <J/kg-m> to reflect the standby energy consumption, or the benchmarking parameter being disabled during midnight.

This parameter encourages the use of intelligent dispatchers by boosting the number of passengers in any trip. An analogy is that although a big bus consumes more energy than a small van, the bus is still considered more energy efficient. It is hoped that in the near future, as soon as a sufficient database becomes available, the industry can have its benchmarking parameter for real-time assessment of the energy efficient performance of any lift system by considering both the motor drives and the traffic control.

7 REFERENCES

Adak M.F., Duru N. and Duru H.T. (2013), "Elevator simulator design and estimating energy consumption of an elevator system", *Energy and Buildings*, Vol. 65, October, pp. 272-280.

Al-Sharif L. (1996), “Lift power consumption”, *Elevator World*, May, Vol. 44, pp. 85-87.

Al-Sharif L., Peters R. and Smith R. (2004), "Elevator energy simulation model", *Elevator World*, November, pp. 108-111).

ASHRAE (2016), *ANSI/ASHRAE Addendum aq to ANSI/ASHRAE Standard 135-2012 Data Communication Protocol for Building Automation and Control Networks*.

Asvestopoulos L. and Spyropoulos N. (2010), “Lifts energy consumption study”, *Elevator Technology 18*, *Proc. 18th ELEVCON*, Luzern, Switzerland pp. 54-59, also published in *Lift Report* 2010.

Barney G. and Al-Sharif L. (2016), *Elevator Traffic Handbook, Theory and Practice*, 2nd Edition, Routledge, London.

Buildings Department, Hong Kong (1995), *Code of Practice for Overall Thermal Transfer Value in Buildings*, http://www.bd.gov.hk/english/documents/code/OTTV-01.pdf.

Doolaard D.A. (1992), “Energy consumption of different types of lift drive systems”, *Elevator Technology 4, Proc. Elevcon 92*, Amsterdam, pp. 214-252.

EMSD (2012a), *Code of Practice for Energy Efficiency of Building Services Installation*, http://www.beeo.emsd.gov.hk/en/pee/BEC_2012%20(Rev.%201).pdf.

EMSD (2012b), *Technical Guidelines on Code of Practice for Energy Efficiency of Building Services Installation,* http://www.beeo.emsd.gov.hk/en/pee/TG-BEC_2012_r1.pdf.

EMSD (2015a), *Code of Practice for Energy Efficiency of Building Services Installation*, http://www.beeo.emsd.gov.hk/en/pee/BEC_2015.pdf.

EMSD (2015b), *Technical Guidelines on Code of Practice for Energy Efficiency of Building Services Installation*, http://www.beeo.emsd.gov.hk/en/pee/TG-BEC_2015.pdf.

Lam, Dante C.M., So, Albert T.P. and Ng T.K. (2006), "Energy conservation solutions for lifts and escalators of hong kong housing authority", *Elevator Technology 16*, *Proceedings of 16th World Congress on Elevator Technologies*, IAEE, Helsinki, June, pp. 190-199.

Lorente-Lafuente A., Nunez-Bruis J.L. and Barney G. (2013a), “Energy models for lifts”, *Elevator World, April*, 2013, pp. 80-99, first presented in 2nd Lift Symposium at Northampton in 2012, England.

Lorente-Lafuente A. (2013b), *Life Cycle Analysis and Energy Modelling of Lifts*, Doctoral thesis, University of Zaragoza.

Lorente-Lafuente A. (2014), “Energy performance of lifts according to ISO 25745-2”, presented in 6th European Lift Congress, Heilbronn.

Peters Research Ltd (2014), Link for Elevate™ Version 8 Manual: https://www.petersresearch.com/index.php/support/manual

Schroeder J. (1986), “Energy consumption and power requirements of elevators”, *Elevator World,* Vol. 34, pp. 28-29.

Siikonen M-L. (2012), "Effect of control systems on elevator energy consumption", presented in European Lift Congress, Heilbronn.

Siikonen M-L., Sorsa J. and Hakala H. (2010), "Impact of traffic on annual elevator energy consumption", *Elevator Technology 18*, pp. 344-353.

So Albert (2014a), “Energy code development, part one”, *Elevator World*, April, 2014, pp. 91-95.

So Albert (2014b), “Energy code development, part two”, *Elevator World*, May, 2014, pp. 76-84.

So Albert, Cheng G., Suen W. and Leung A. (2005), "Elevator performance evaluation in two numbers",
Elevator World, Vol. LIII, No. 1, January, pp. 102-105.

So, A. and Wong C.T.C. (2012), "Implementation of counterweight adjustment to achieve energy savings", *Elevator Technology 19*, *Proc. Elevcon 2012*, IAEE, Miami, May, 2012, pp. 185-192.

Yeung K. and Lau O. (2011), "Building energy code – the way towards low carbon building", *Prof. EMSD Symp on E&M Safety & Energy Efficiency*,
"http://www.emsd.gov.hk/filemanager/conferencepaper/en/upload/33/EMSD_SYMPOSIUM_BEC_Full%20Paper_R9.pdf.

BIOGRAPHICAL DETAILS

Ir Dr. Albert So is an executive board member and scientific advisor of the International Association of Elevator Engineers (IAEE). He is the honorary visiting professor of the University of Northampton in the U.K. He serves on the Advisory Group of Elevator World, Inc., and is based in Seattle.

Ir Ricky Chan is currently a visiting lecturer in the City University of Hong Kong and a PhD candidate at the University of Northampton, U.K.

Professor Dr. Stefan Kaczmarczyk is Professor of Applied Mechanics and Postgraduate Programme Leader for Lift Engineering at the University of Northampton.