Evaluating a Holistic Energy Benchmarking Parameter of Lift Systems by using Computer Simulation

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Keywords: Energy consumption, benchmarking parameter, lift traffic, lift drive, normalization, computer simulation

Abstract. At present, there are benchmarking parameters to assess the energy performance of lifts , e.g. one in Germany adopted by VDI (4707-1/2), one internationally published by ISO (BS EN ISO 25745-2:2015), and the other in Hong Kong adopted by The Hong Kong Special Administrative Region (HKSAR) Government. These parameters are mainly checking the energy consumed by a lift drive without considering real time passenger demands and traffic conditions; the one in Hong Kong pinpointing a fully loaded up-journey under rated speed and the two in Europe pinpointing a round trip, bottom floor to top floor and return with an empty car, though including energy consumed by lighting, displays, ventilation etc. A holistic normalization method by Lam et al [1] was developed a number of years ago by one of the co-authors of this article, which can assess both drive efficiency and traffic control, termed *J/kg-m*, which is now adopted by the HKSAR Government as a good practice, but not specified in the mandatory code. In Europe, the energy unit of Wh has been used but here, Joule (*J*), i.e. Ws, is adopted to discriminate the difference between the two concepts. In this article, this parameter is evaluated under different lift traffic scenarios using computer simulation techniques, with an 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.

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 only correct when a commercial office building is considered, but not 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 [2]). According to Lift Report [3], 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, and the type and number of lifts. The report published in 2010 estimated that there were around 8.5 million lifts in operation worldwide. In 2016 this figure should be close to eleven to twelve million, with an estimated growth of around 670,000 per year.

Schroeder [4] developed a generalized formula to calculate the annual energy consumption of lifts per square metre of building space. Doolaard [5] compared the relative consumption of energy by hydraulic lifts, AC-2 lifts, and ACVVVF lifts. Al-Sharif [6] 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.

In this paper, a review of various issues regarding energy efficiency is made, with particular reference to the mandatory *Building Energy Code* (*BEC*) 2015 [7] in Hong Kong and the guideline [8], BS EN 25745-2. This paper aims to provide a holistic energy efficiency benchmarking parameter that covers all types of drives, including but not limited to AC2, ACVV, DCWL, DCTL, ACVVVF (scalar and vectored), PMSM, linear machines, hydraulic etc.

2 LITERATURE SURVEY

2.1 VDI 4707 and ISO 25745-2

The first energy guideline for lifts and escalators could refer to VDI 4707 initiated in Germany with guidelines published by the Association of German Engineers (VDI), a draft of which appeared at the end of 2007. It classifies lift performance into seven categories, "A" the best and "G" the worst. The classification is based on two measurements, namely "travel" and "stand-by". A mathematical procedure is employed to analyze the measurement with reference to usage category, speed, rated load and travel height to arrive at the classification. The "travel" demand is the total energy demand of the lift during trips at specified trip cycles and with a defined load while the resultant specific demand value is given in mWh/m-kg. Four usage categories were defined, namely "low", "medium or occasionally", "high or frequently" and "very high or very frequently". The actual procedures of measurement and analysis are detailed in ISO 25745-1 and ISO 25745-2. In our study, J/kg-m is consistently adopted due to the big difference between the two concepts.

The terminal landings cycling test is defined in Clause 2.18 of ISO 25745-1:2012, stating that the empty car is continuously cycled between the bottom terminal landing and the top terminal landing, with the door operations enabled. Section 4 of ISO 25745-2 further defines running energy measurements in two ways, the one between two terminal landings with two complete door cycles (termed a reference cycle), or the one between two predetermined landings with two complete door cycles (termed a short cycle). Based on the running energy of a reference cycle, Erc, and the running energy of a short cycle, Esc, and their corresponding one-way travel distance, src and ssc, the average running energy consumption per metre of travel, Erm, can be estimated by equation (1).

$$E_{rm} = \frac{1}{2}\left(\frac{E_{rc} - E_{sc}}{s_{rc} - s_{sc}} \right) \tag{1}$$

From this Erm, other parameters such as Essc (start/stop energy consumption for each trip), Erav (running energy of an average cycle) and Erd (daily running energy) etc. can be evaluated.

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* [9] 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. In 2012, the four codes, and others, were combined into one document, *Code of Practice for Energy Efficiency of Building Services Installation*, called *BEC* in short [10]. Under the enforcement of the *Building Energy Efficiency Ordinance* Cap 610 in the same year, this combined code of practice became mandatory in Hong Kong. All new and extensively retrofitted buildings need to comply with the code of practice. By 2015, the code was slightly revised with some tightened clauses and published in 2015 [7]. As a companion to the code, a set of guidelines was also published by the EMSD [8].

The item in the *BEC* that is closely related to ISO 25745 may perhaps be the limit of maximum allowable electrical power of motor drives. Inside the *BEC*, tables provide the maximum power of a motor drive with respect to the rated load and the rated speed of a lift as measured under a fully loaded rated speed with upward movement. There are separate tables for hydraulic lifts, escalators and passenger conveyors.

2.3 The proposed Benchmarking Parameter, J/kg-m

So far, it can be observed that all existing international standards or national guidelines mainly concern the efficiency of the lift along a standard trip, either no-load or full-load. But we should be aware that most real journeys are neither full loaded nor no loaded. The Hong Kong *BEC* concerns the power consumption, not accumulated energy, during a full-loaded rated speed up journey although under some circumstances regenerative braking is mandatorily required. ISO 25745-2 concerns the whole reference cycle by measuring the accumulated energy during both no-loaded up and no-loaded down journeys, including acceleration, deceleration and rated speed operation. If regenerative braking is employed, its performance is also included in E_{rc}. Having said that, assessment by the two schemes is restricted to the motor drive alone.

One of the authors of this paper, together with other researchers, raised an argument some eleven years ago by So et al [11] that merely an energy efficient motor drive is not the ultimate solution to an energy efficient lift system. Efficiency of the drive can only account for the hardware performance, whereas the main saving should come from supervisory traffic control. In that 2005 paper by So et al [11] 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 must take care of both the physical drive performance as well as the soft traffic control algorithms. Therefore, the idea of *J/kg-m* was suggested.

The basic concept of *J/kg-m* is simple. It is the average energy required to convey one unit of mass, passengers or goods, a distance of one metre, irrespective of direction over a fixed and agreed period of time. An energy efficient motor drive can of course lower such an average value, but an energy efficient supervisory control system can lower the value by a more significant amount, the illustration of which is the main theme of this paper. To evaluate this benchmarking value, three measurements have to be made:

i) energy consumed, in Ws or *J*, over the fixed period of time, *T*, say 2 hours (7200 sec) long;

ii) mass of load, in kg, inside the car, at any time within *T*;

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

This parameter has been included in the guideline of the *BEC* published in 2012 by EMSD [8] 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 the 2015 *BEC*) [7], (ii) and (iii) are usually not readily available to the lift owner or user. Thanks to the publication of the recently approved BACnet objects through ASHRAE [12] for lifts and escalators, all three can be obtained by the appropriate implementation of the relevant BACnet objects.

Within the period of time from 0 s to *T* s, say two hours, i.e. 2 * 3600 = 7200 s, there could be *N* number of brake-to-brake journeys of one car or several cars belonging to the same bank. The *i*th 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 park 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 goes on and on. 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 and indication etc. Eventually, one *J/kg-m* (*k*) value can be found for each *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 (2) is valid. Any brake-to-brake journey across the two limits of the *k*th period could also be included in equation (2) as it does not affect the statistics by much.

$$\mathrm{J/kg\ -\ m}\ (k) = \frac{E_T(k)}{\sum_{i=1}^{N} w_i(k) d_i(k)} \tag{2}$$

3 VALIDATION OF THE BENCHMARKING PARAMETER BY SIMULATION

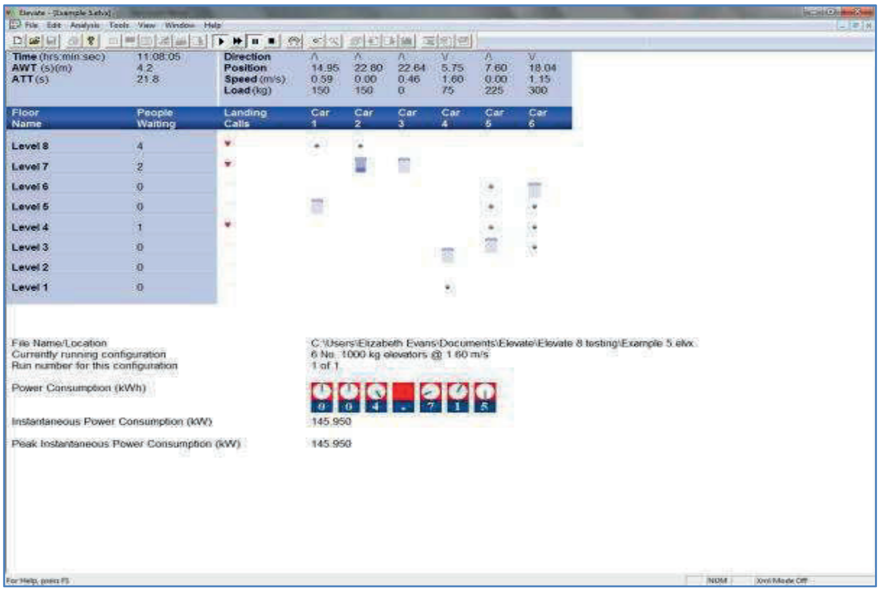
3.1 Background of the simulation software

As described and defined earlier, the advantage of the benchmarking parameter, J/kg-m, is that it can tell at a glance whether the energy consumption of the lift is within a well-established and well-recognized energy efficient range. But how to find out this benchmarking figure as a reliable and convincible iconic number for reference by the lift industry and professionals needs great effort to carefully assess the quality of service for existing lift installations, said Richard Peters based on Strakosch and Caporale [13]. He again said that assessing lift transportation to know the exact passenger demand was not an easy task.

To know the passenger demand more precisely, we need to quantify the lift traffic, and most important is to know how to measure it. Before the advent of this software, the previous researchers might try to clamp the traffic analyzers in the lift control systems to log on the operational data. For the passenger demand, they could simply do manual traffic surveys. All these methods were suggested by Richard Peters with Strakosch and Caporale [13]. The latter however are so laborious and time consuming by waiting in the lift lobby and inside the lift cars to count the numbers of passengers in their waiting and transit times. Fortunately there was a very good simulation tool [14] which has been developed since 1989 from its first version, and now been upgraded to its 8th version.

The features of this software include all functions of previous versions, with a newly added real-time instantaneous energy consumption, kWh = 3,600,000 J. Through this added energy function, we can make the evaluation and assessment of the benchmarking parameter, the *J/kg-m*, feasible. That means that the instantaneous power consumption, kW, has become part of the data display during analysis consumed in every single time interval, say five minutes of the lift, either in its up-peak, inter-floor or down-peak operation throughout the simulation. Figure 1 below indicates the simulation display with real-time animation of those input lift cars, four of them, going up and down during the simulation. To make this energy consumption more accurate, all the mandated inputs on building data, lift data and passenger data must be checked and inputted with care. Then the energy consumption (kWh) and the instantaneous cumulative power consumption (kW) are indicated in graphical form as the gauges displayed near the bottom of the slide in Figure 1.

The fundamental and advanced functions of using this software to do the design work, such as to find out the round trip time, the average transit time, average waiting time and queue lengths, etc. will not be mentioned in this exercise. In this paper, the main concern is to use different scenarios to test the benchmarking parameter, *J/kg-m*. It is obvious that the smaller the value of the *J/kg-m* , the more energy efficient the lift (So et al) [11].



Time (hrs:min:sec) 11:08:05
AWT (s)(m) 4.2
ATT (s) 21.8

Direction	^	^	^	v	^	v
Position	14.95	22.80	22.64	5.75	7.60	18.04
Speed (m/s)	0.59	0.00	0.46	1.60	0.00	1.15
Load (kg)	150	150	0	75	225	300

Floor Name	People Waiting	Landing Calls	Car 1	Car 2	Car 3	Car 4	Car 5	Car 6
Level 8	4							
Level 7	2							
Level 6	0							
Level 5	0							
Level 4	1							
Level 3	0							
Level 2	0							
Level 1	0							

File Name/Location C:\Users\Elizabeth Evans\Documents\Elevate\Elevate 8 testing\Example 5.elvx
Currently running configuration 6 No. 1000 kg elevators @ 1.60 m/s
Run number for this configuration 1 of 1
Power Consumption (kWh) 0 0 4 . 7 1 5
Instantaneous Power Consumption (kW) 145.950
Peak Instantaneous Power Consumption (kW) 145.950

Figure 1: The simulation display with the feature on lift power consumption

4 RESULTS AND ANALYSIS

4.1 Raw data converted to spread sheet for analysis

Table 1 below illustrates the output from the simulation software regarding brake-to-brake journeys with details such as time, position, load etc. Finally when the individual time spent by journeys of the four lifts is known, and their corresponding traveled distances, the parameter, the *J/kg-m* at the prescribed moving time period or window can be made available. Table 2 shows how *J/kg-m* is evaluated after the energy consumed and the load-distance products are known.

Table 1 Part of the Raw Data extracted from the simulation results of the four lifts

Lift no. (1~4)	Time (sec)	Readable Time In (hr:min:sec) =Time/3600	Floor (21 story)	Load (kg)	Traveled Dist. (m)	From/To	Floor	kg*m	Time used (s)
1	27946.1	7:45:46	1	75		From	G/F		
1	27974.4	7:46:14	16	75	60	To	F16	4500	0:00:28
1	27982.3	7:46:22	16	0		From	F16		
1	28010.6	7:46:50	1	0	60	To	G/F	0	0:00:28
1	28142.2	7:49:02	1	0		From	G/F		
1	**28148**	**7:49:08**	**2**	**0**	**4**	**To**	**F2**	**0**	**0:00:06**

Note: The shaded heading in grey was the raw data generated from the software

Table 2 One of the calculation examples of J/kg-m vs. moving time period

Moving Time Period or Window	Sum of J	Sum of Total kg*m	*J/kg-m*	Average
8:45	258057010.8	5105700	50.542925	-
9:00	257868597.3	5414400	47.62644	43.383857
9:15	252151793.9	5643300	44.681621	43.383857
9:30	246846141.8	5825400	42.37411	43.383857
9:45	243568562.3	5928300	41.085735	43.383857
10:00	229031523.7	5676000	40.350867	43.383857
10:15	232685791.1	5448900	42.70326	43.383857
10:30	232426069.8	5165100	44.999336	43.383857
10:45	224709987.8	5061600	44.395051	43.383857
11:00	222824627	5440500	40.956645	43.383857
11:15	212200154.6	5657700	37.506435	-

This energy model is available to simulate the energy use of the lift in question traveling at up peak, down peak and inter-floor traffic patterns. Inputs are available when this energy model has been converted to the analytical data, say, in spread sheet format. For each lift car, the power consumed during a journey can be defined for different passenger loads, say at its 0, 20, 40, 60, 80 and 100% in both up and down directions.

4.2 Simulation in lift traffic control and energy consumption

In the simulation work of this paper, different lift operating scenarios were attempted, i.e. using different sets of the lift configurations; such as the building data, the lift data and finally the passenger data. Subject to limitation in space of this paper and the intention of illustration, the input scenarios were limited to four, i.e. from Figures 2 to 5. The last figure (Figure 5) was purposely tried to include some unreasonable and uncommon scenarios to test what simulated result would come out.

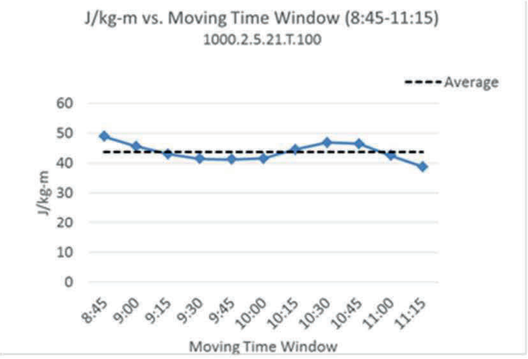


Figure 2 1000 kg, 2.5 m/s, 21 stories, full loaded simulation

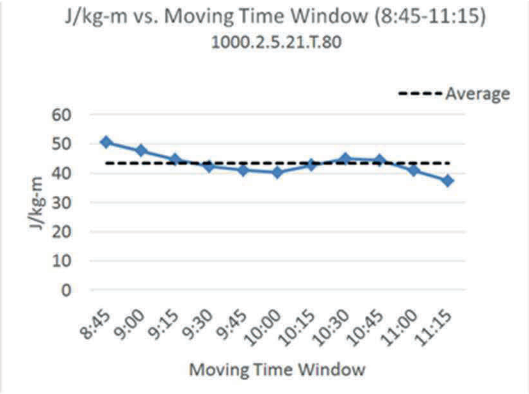


Figure 3 1000 kg, 2.5 m/s, 21 stories, 80% loaded simulation

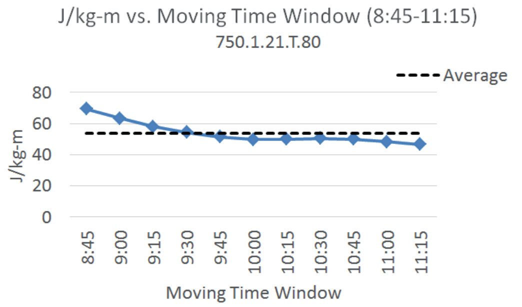


Figure 4 750 kg, 2.5 m/s, 21 stories, 80% loaded

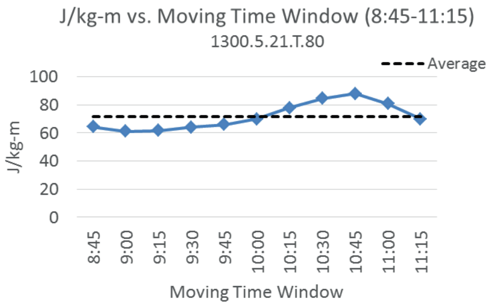


Figure 5 1300 kg, 5.0 m/s, 21 stories, 80% loaded simulation (purposely over-designed)

The time scale in running these simulations is from 07:45 am to 12:15 pm but the first 15 and last 15 minutes are ignored. With *T* = 2 hours and a running increment of 15 minutes, there are nine reasonable values (though 11 data points displayed) of simulations during a 4.5 hour time window. The first and last points in the four figures should be ignored. The first useful value represents the period from 08:00:00 to 09:59:59, thus centered at 09:00:00. The second value represents the period from 08:15:00 to 10:14:59, thus centered at 09:15:00, until the last moving time period at 11:00.

During this 4.5-hour simulation, it is expected that the *J/kg-m* values are high during the first 2 hours due to up-peak and this can be explained through common sense. In the morning, lift riders are rushing to commence work to their offices. During up-peak, up journeys are close to full loaded as the motor is also working at full load. Down journeys are also close to full load. The J-parameter value would lie in the middle range, as during the coming one-hour, staff would use the lifts up and down as their inter-floor journeys, in particular for those offices, clinics, law firms, etc, that occupy several floors under the same companies, and so they need to travel within their own occupied floors. A low value of *J/kg-m* is expected during the last 1.5 hour in the morning session, indicated as down-peak, such as lunch time or for the half-day workers in these lift riding cycles. During down-peak, every journey is closed to full-loaded down, irrespective of the actual moving direction.

5 CONCLUSIONS

After completing these few simulations by using the software [14] with the power consumption feature at different lift operating scenarios, a series of the benchmarking parameter values in *J/kg-m* was collected, though the sampling size in this exercise was not enough to secure a publicly acceptable standard. Yet from the graphs, a preliminary conclusion could be drawn with some confidence. Whenever the lifts are designed at rated capacity of either 750 or 1000 kg and an operating speed of 2.5 m/s, under traveled distance at about 80 metres, i.e. 21 stories, the *J/kg-m* value does not fluctuate too much. Though Figure 5 shows an average of 70 *J/kg-m* which seems to be quite high comparatively, in fact, it is a special case to simulate an over designed scenario. Apparently this small simulation work could at least demonstrate the concept of using *J/kg-m* as a benchmarking parameter that could well agree to the statements as So et al said [11]. Furthermore, a reasonable value could be suggested at 50 *J/kg-m* as stated in the BEC Technical Guidelines [8], which is well supported by our simulation works here, i.e. 43 *J/kg-m* on average (Figure 2 and 3) and 52 *J/kg-m* on average (Figure 4).

The over designed scenario as reflected from Figure 5 at an unreasonable high rated speed of 5 m/s and rated capacity of 1,300 kg is further explained here. In this trial design figure, when a larger lift motor is used, more power is consumed no matter under whatever traffic conditions. That is why a higher *J/kg-m* value is obtained in the simulation. By the way, the pattern of curves depicted in Figures 2, 3 and 4 is quite steady by itself, but it is quite different in Figure 5. The curve in Figure 5 shows surprisingly low *J/kg-m* value during up-peak, while it is flat during the inter-floor traffic, and relatively high at down-peak. That means it is quite different from those with normal or reasonable design scenarios, except a steady J-value appears during the inter-floor traffic period, but it has a comparatively high *J/kg-m* value during the lunch time. Probably, during down-peak, cars are not fully loaded due to its big rated capacity at 1300 kg and therefore regenerative energy is not enough to compensate the energy consumed by the lift motor.

Further works are suggested to conduct more simulation tests with broader range of scenarios and combinations of the input parameters/data with different design configurations in terms of rated capacity, rated speed, zoning and passenger demands. Finally going back to the argument whether Wh, mWh or Joule (Ws) would be used for the benchmarking parameter, the authors would like to have a more obvious demarcation between ours and the currently used European parameters because the concepts between these two are totally different; ours being on real-time measurement with more complicated traffic patterns, while the European or Hong Kong ones being on fixed load patterns.

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BIOGRAPHICAL DETAILS

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