CAFEO 33 IPT-01 from Design to Operation: Practical Experience of Lift Engineering

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Abstract: This paper shares practical experience of lift business process and lift system design. Early involvement of lift engineer during tendering stage before finalization of architecture design of building is essential to ensure that the vertical transportation system is designed to cope traffic demand. Criterion to be considered are handling capacity of lift system and also average waiting time of passengers. Upon finalization of the specification such as load, speed, number of floors etc, detailed specification shall be established to ensure that factory will design and manufacture the lift meeting specification. Some key designs such as roping configuration, machine sizing, rope sizing, cabin design, and layout drawings are discussed. The lift system must be designed in compliance with safety and regulatory codes. The design outputs are shop drawing and bills of material for manufacturing and procurement processes. Lift supplier will be responsible to submit design of lift system authority for approval prior to installation. It is emphasized that good project management is crucial to ensure schedule of equipment delivery, installation, testing and commissioning, authority inspection and handover of lift will follow master schedule of the building without compromising safety and health of stakeholders involved. Regular site meeting is required to ensure that factory is kept informed on the building progress so that entire supply chain could be managed efficiently. Besides that, any change initiated by customer could also be managed to reduce risk on schedule and cost.

Introduction

Lift is the important element inside building, it facilitates traffic flow inside building. In 1853, invention of safety gear by Elisha Otis (founder of Otis Elevator) opens up new chapter of modern history of lift design and makes construction of skyscrapers possible. Apart from safety gear, rapid development of electromechanical technology in also plays crucial role in bringing design of lift from steam powered to electrical motor driven. Since 1920s, engineers already laid down strong foundation to design and develop sophisticated electric lifts to meet the demand of booming construction of high rise building particularly in New York and Chicago. Reed presented a significant paper that outlines fundamental design guide of electric lift (Reed, 1922) as following:

- The lift car (or known as cabin) comprises enclosed platform secured to car frame and equipped with safety devices
- The lift shaft consists of guide rails, counterweight, limit switches and other devices
- The hoisting machine with motor, brake, controller and wirings

The roping of lift with full wrap (also known as double wrap) traction and half wrap (also known as single wrap) traction in Figure 1.

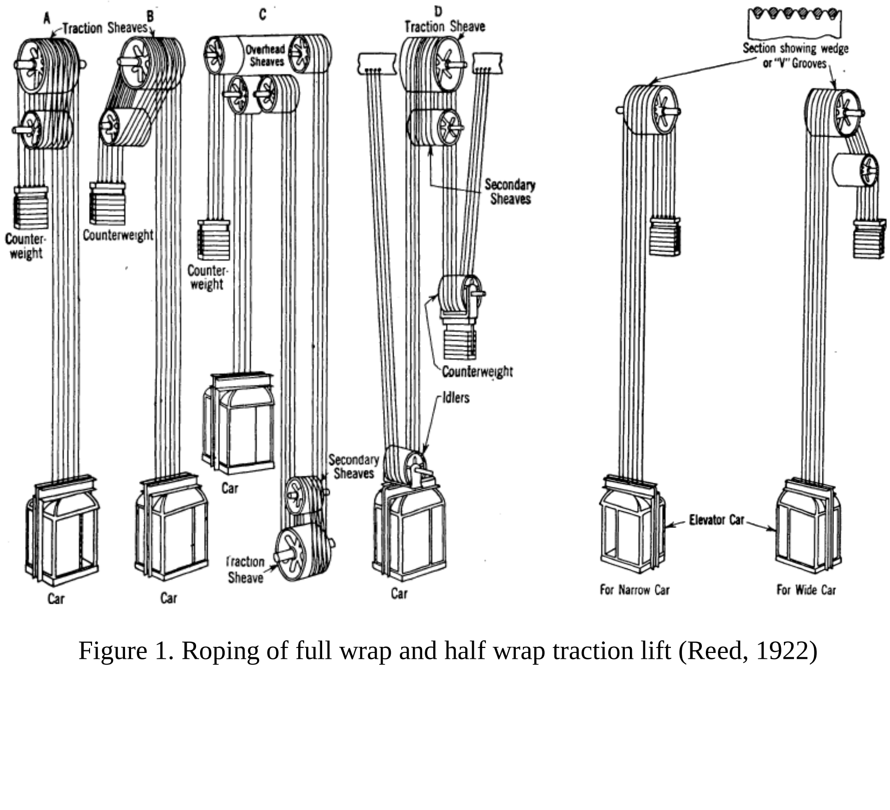


Figure 1. Roping of full wrap and half wrap traction lift (Reed, 1922)

In 1924, Marryat studied traffic pattern of building and proposed systematic method to calculate lift capacity (Marryat, 1924). The variable voltage system is used to regulate speed of lift by using motor generator (Bouton, 1924), this has improved riding comfort of passenger remarkably. Malaysia have the first elevator supplied by Otis installed in E & O hotel in Penang (www.otis.com/site/my). In 1940s, Atkinson presented design and construction of modern electric lift in his paper (Atkinson, 1945), he discussed important features of modern lifts including layout of lift shaft, contract load and speed of lift to suit application and serve traffic demand, construction of lift car, landing doors, control system, safety devices, traction machine, and operation. This basically set the ground rules for designing of lift we are seeing today. The modern lift construction is illustrated in Figure 2.

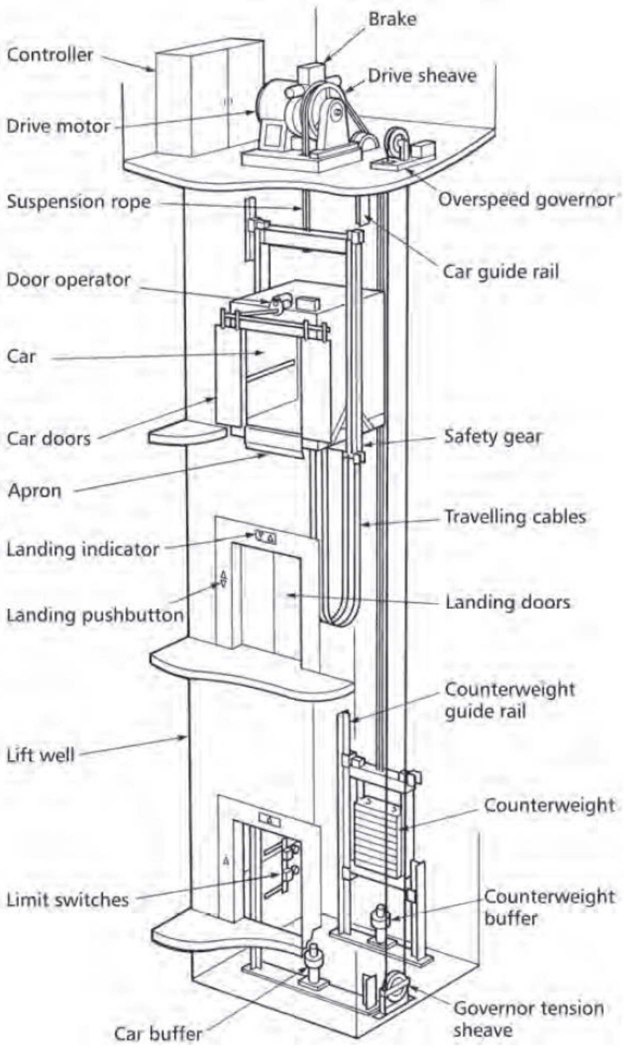


Figure 2. Construction of electric lift (CIBSE Guide D)

Business Process of Lift Industry

Every industry will have its business process, business of lift industry covers sales, design, manufacturing, installation and maintenance as shown in Figure 3, which is similar like other building service equipment like air conditioning system. Core functional departments and stakeholder of lift company are depicted in Table 1.

Sales will the department to liaise with client, usually consulting engineer to secure the business with technical support from Engineering. Upon awarding of contract to supply lift, Sales department will prepare customer specification list which clearly specifies customer requirements, typically number of floors, capacity, speed, number of car and landing openings, finishes of car door, landing door, interior design of lift car, design of hall position indicator, type of button (round or square), type of car operating panel and hall call panel, some features are optional such as braille letterings on car operating panel and hall panel, LCD display, voice announcer, handrail, hall lantern, etc. Information from this customer specification list will be stipulated in shop drawing, it will be master document for project implementation. Figure 3 shows basic items lift car design, car operating panel and hall panel that client could make a choice by considering mainly budget, aesthetic of lift to harmonize with building design and location of lift to be installed. Typical example could be seen is lifts in main lobby are with etched stainless steel wall mean while car park lifts are with epoxy painted wall. Any change after finalization of customer specification will be handled via change management in which variation order will be initiated.

The contract will then be passed to Project to execute the contract. In general, most of lift company adopts matrix structure, Project will be the window between client and internal departments such as Sales, Engineering, Production, competence person and Maintenance. It is also common that tester and adjuster responsible for testing and commissioning of lift at site also attached to Project. Regular site meeting is crucial to ensure that building construction is closely monitored so that Project could arrange equipment delivery with factory. It is common arrangement that machine room equipment such as traction machine and control panel will be hoisted up into machine room by tower crane before roof work is completed. Subsequent equipment delivery will be made upon handover of lift shaft in a condition suitable to commence of installation. Project also need to verify that shaft is constructed in accordance to shop drawing to prevent problem in installation later. It is emphasized that installation is very important process in lift operation, poor installation such as unaligned guide rails will lead to jerking ride. Besides that, installation workers are also explored to various hazards at site. Hence, comprehensive quality check and safety measures have to be taken to assure quality of installation and safety of workers.

Table 1. Stakeholders in lift company

Department/Stakeholder	Function
Sales	To secure business and finalize contract with client
Project	To execute contract of lift supply, regular site meeting with client to align activities related to lift installation aligned progress of building construction, clarify and resolve deviation with client, coordinate with Engineering for the revision of specification, coordinate with Production for equipment delivery to site, coordinate with subcontractor for installation and testing and commissioning work, coordinate with competence person and client for first schedule inspection with department of occupational safety and health (JKKP), to hand over lift to Maintenance upon receiving of certificate of fitness (CF) from JKKP
Engineering	To prepare shop drawing for submission to client, prepare design drawing and bills of materials (BOM) for production and procurement of equipment, provide technical support to other departments
Production	To manufacture and assemble component of lift, coordinate equipment delivery to site
Competence person	To advise Engineering on design and safety code to internal departments, submit first schedule of lift installation to JKKP for approval, attend inspection with JKKP inspector to ensure that performance and safety device of lift achieve satisfactory level prior to release for public use, investigate accident and report to JKKP
Maintenance	To service and maintain lift based on contract with client, coordinate and attend second schedule with JKKP inspector annually to renew CF, explore business opportunity of lift modernization with client

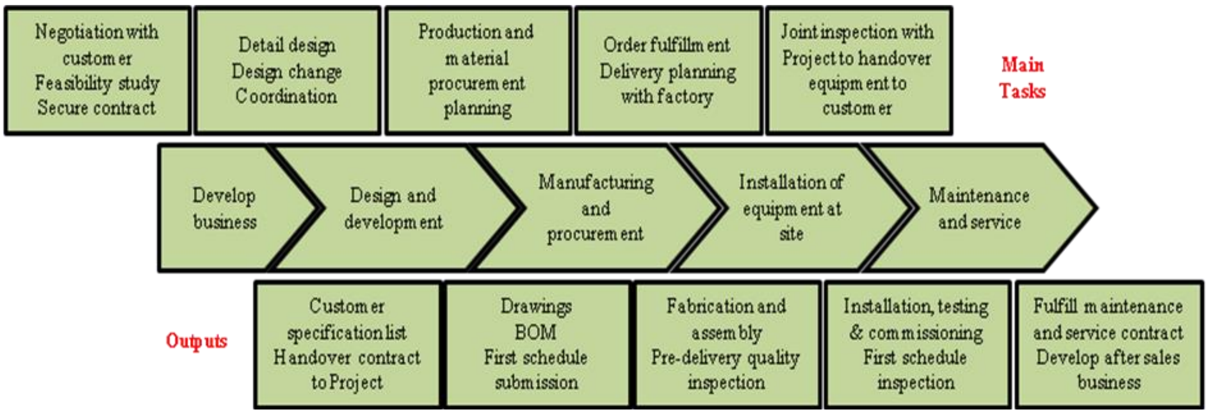


Figure 3. Typical business process of lift industry

In Malaysia, design of electric passenger and goods lift shall comply with Factory and Machinery Act (FMA). Lift competent person registered with department of occupational safety and health (JKKP) will need to submit detail specification of lift to be installed in first schedule submission. The lift has to be inspected by factory and machinery inspector and competent person to ensure compliance with FMA and hazards are removed prior to issuance of certificate of fitness. This ensures that public safety is safe guard. Figure 4 shows example of first schedule.

Figure 3. Car design, type of car operating and hall panel (Source: www.mitsubishielevator.com)

FIRST SCHEDULE
FACTORIES AND MACHINERY (ELECTRICAL PASSENGER AND GOODS LIFT) REGULATIONS, 1970
Regulation 6 (a)

PARTICULARS OF ELECTRIC	[redacted]
Name and postal address of Owner	[redacted]
Name and postal address of manufacturers	[redacted]
Lift to be installed/altered at	[redacted]
Name and address of installing firm:	[redacted]
No. of floor served	LG, G, 1 ~ 8 (10 stops) Total Travel : 33895 mm Contract Speed : 60 mpm
Contract Load	1365 kg Motor Horse Power : 15kw Power : AC/Drive : Traction, Geared/~~Gearless~~
Lift Serial No.	
Drawing No.	PG - 1/05/005/13D & 14D
Operation	Two car group control
Control	Variable Voltage Variable Frequency (V.V.V.F)

	Regulation	Particulars		FOR OFFICIAL USE ONLY Requirements	Chief Inspector's remarks	Inspector's check figure	Inspector's remarks
Lift loading capacity	7 (2) (a)	Passenger lift car floor area No. of persons Contract load	**3.13** sq. metre **20 persons** **1365** kg.				
	7 (3)	Type of goods lift Minimum contract load/sq. meter	**N/A** **N/A**				
Lift machine and supports	8 (1) (2)	Type of driving machines..	**Traction**				
	8 (3)	Method of connecting main driving gear to drum or traction sheave	**Worm Gear Unit**	Friction gearing or friction clutch mechanism not permitted			
	8 (4)	Material for worms and worm gears	**Chromemolybdenum steel for the worm shaft and phosphor bronze for worm gear**	Cast iron not permitted			
	8 (5)	Method of fastening used where connection is subject tension or torsion	**By bolts & nuts**	Set-screw fastening not permitted Cast iron			
	8 (6)	Material for drum, sheave or pulley	**Cast iron**	Cast iron or steel			
Lift machine and supports	8 (7)	Diameter of drum, sheave or pulley	**710**				

Figure 4. Example of first schedule

Traffic Requirement of Lift System

In the design stage, it is crucial for lift supplier to understand requirement of vertical traffic flow and demand in the building. Type of building, number of floors, estimated population and lift arrangement inside building are key inputs for lift system design. Traffic analysis is particularly important in commercial building due to nature of operation that exhibits typical traffic pattern with morning up peak, evening down peak and inter floor traffic.

There will be a critical 5 minute where staffs will be rushing to work place before commencement of office hour during morning up peak as illustrated in Figure 5. In general, CIBSE guide D will be used as main reference when designing traffic. Lift system shall be designed in such a manner to meet 5 minute handling capacity ratio (5MHCR) and average waiting time (AWT) requirements. 5MHCR and AWT are quantitative and qualitative performance respectively of lift system. AWT is average time passenger need to wait for lift to serve him upon arrival to main floor, meanwhile 5MHCR is the handling capacity of lift system with ratio to total population of tenants inside building in critical 5 minute of morning up peak. In usual case, lift supplier shall obtain population from building designer. In some case, where this information is not being defined, good estimation would be acceptable, 12m^2 net area/person.

The first parameter to start traffic analysis is round trip time (RTT). RTT is the total time consumed for the lift to make a round trip to serve average stop floors. RTT starts when the lift door closed at main floor and then ends when it reaches main floor and then open door to discharge passengers. RTT is illustrated in Figure 6 for typical building.

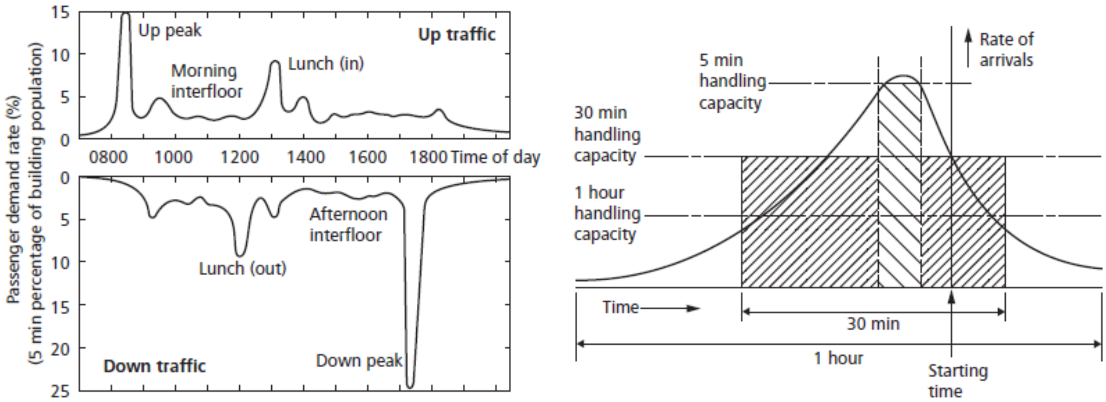


Figure 5. Typical traffic pattern of the office building and critical 5 minute of morning up peak

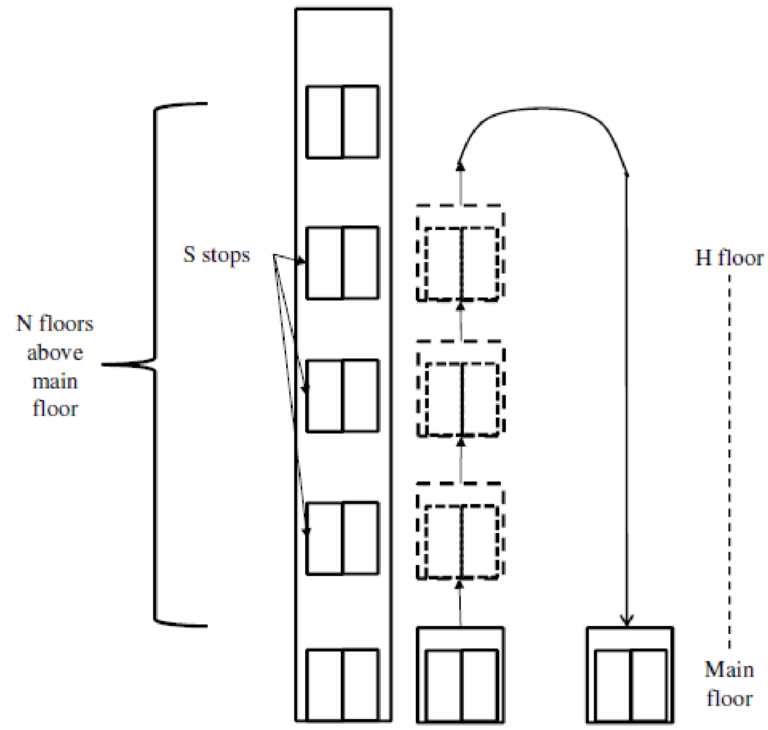


Figure 6. Round trip time (RTT) of the lift

RTT could be obtained analytically as recommended by Barney published in Elevator Technology.

$$RTT = 2H\,t_v + (S+1)t_s + 2P\,t_p \qquad (1)$$

where t_v is time of lift traveling between floors, $t_v = t_a + \frac{d}{v} + t_d$, t_a and t_d are acceleration time and deceleration time respectively, t_s is total time for lift door opening $t_{d\,o}$ and closing $t_{d\,c}$ which is much dependent on width of opening and type such as center opening and side opening, $t_s = t_{d\,o} + t_{d\,c}$

t_p is total time for passenger to access $t_{p\,i}$ into and go out $t_{p\,o}$ from lift, $t_s = t_{p\,i} + t_{p\,o}$
d is floor height and v is rated speed of lift itself
S is average number stops

$$S = N\left[1 - \left(1 - \frac{1}{N}\right)^P\right] \quad (2)$$

H is the highest reversal floor

$$H = N - \sum_{i=1}^{N-1}\left(\frac{i}{N}\right)^P \quad (3)$$

P is the average number of passengers carried by lift, it is common to express P as 80% of rated load, this is reasonable approximation. After having RTT, up peak interval INT could be calculated

$$INT = \frac{RTT}{L} \quad (4)$$

where L is number of lift in the same group control. With lift loading of 50% - 80%, AWT is therefore calculated

$$AWT = \left\{0.4 + \left[\left(1.8 \times \frac{\%L}{100}\right) - 0.77\right]^2\right\} INT \quad (5)$$

5 minute handling capacity (5MHC) is therefore

$$5MHC = \frac{5 \times 60}{INT} \times P \quad (6)$$

finally, 5MHCR is calculated

$$5MHCR = \frac{5MHC}{population} \times 100\% \quad (7)$$

The above equations are meant for equal floor height, more complicated equations could be found in CIBSE guide D. From above equations, number of lift in the same group could reduce INT and RTT. Therefore, it is a common approach to increase number of lift L to fulfill AWT ≤ 30s. It is important to note that increasing capacity of lift does not guarantee satisfactory AWT based on Equations (2) and (3), $P \uparrow$ implies that $S\uparrow$ and $H\uparrow$, therefore it leads to longer RTT. Besides number of lifts, speed is also a factor that could contribute to lower RTT. However, in certain cases, the influence of speed might not be significant, for example, for building with 10 floors, speed of 105mpm shall be more than adequate, further increase of speed might not be meaningful, simple reason is lift will have rare chance to achieve full speed because it will start decelerating based on S and H. The ideal 5MHCR for office building is 10-15%. Today, traffic analysis could be easily done by using sophisticated software so that lift engineer could work together with architect to design building with smooth vertical traffic flow. The process of lift system design at early stage is illustrated in Figure 7.

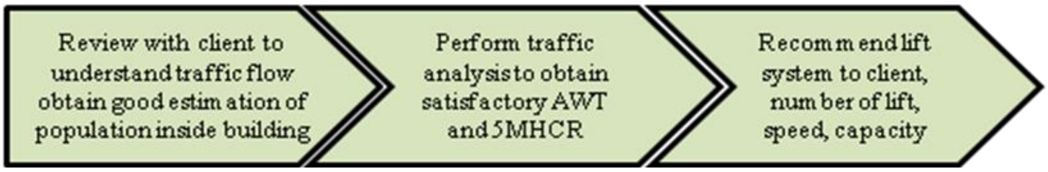


Figure 7. System design of lift to fulfill traffic requirement

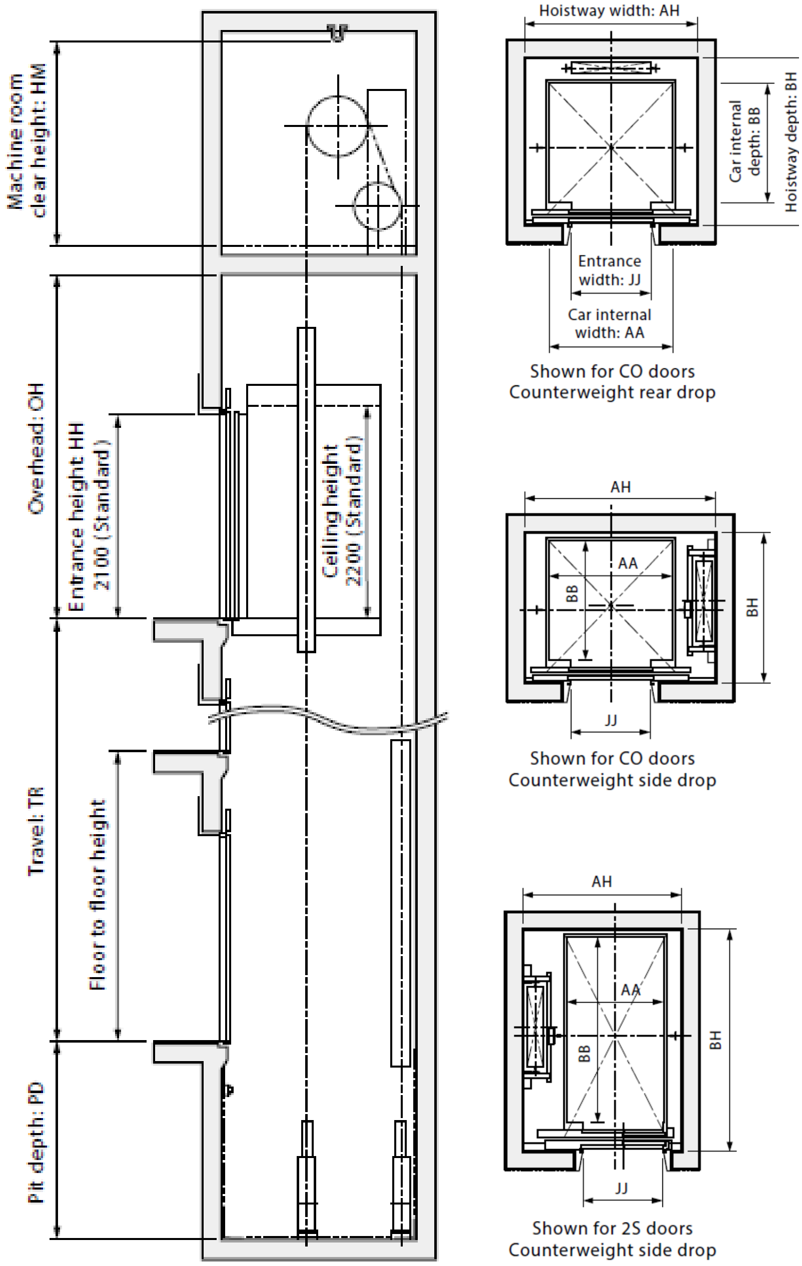
Design of Lift System

In most of the cases, lift company will also provide sketches which illustrate layout of lift arrangement. Layout design of lift is also another interesting topic. arrangement of lift inside shaft shall complied with regulation, Dimension of overhead and pit have to be carefully calculated so that clearance stipulated in FMA during over run of lift or lift fully compresses on buffer are observed. This is to ensure that sufficient clearance available so that person working at car top or pit will survive in the event of lift over run due to severe malfunction. Figure 8 shows typical lift shaft layout and construction of lift car.

The minimum overhead could be calculated considering lift over run in ascending direction and counterweight buffer is fully compressed. The minimum top clearance in general design is 2ft calculated from top crosshead to machine room slab.

$$OH = CH + RB + BS + 150 + \frac{1}{2}RB \quad (8)$$

where OH is overhead, CH is the height of lift car measured from platform to top crosshead, RB (run by) is clearance between counterweight frame and counterweight buffer, BS is counterweight buffer stroke. On the other hand, the minimum clearance at lift pit measured from bottom crosshead to pit floor when car buffer is fully compressed is 610mm. In accordance to FMA, for lift with speed ≤ $1ms^{-1}$, spring buffer could be used, meanwhile, for speed > $1ms^{-1}$, oil buffer has to be employed. Besides that overhead and pit depth requirements, arrangement of lift in shaft also needs understanding of lift components and FMA. In any design, it is always a fundamental approach to propose standard lift with square shape. Main advantage of square lift is efficient people flow compared with stretcher lift as shown in Figure 9 in which passengers in stretcher have to line up in more rows, it also provide more flexibility in interior design of lift car, for instance ceiling type.



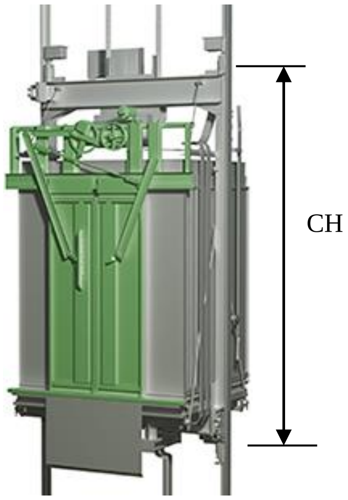


Figure 8. Typical layout of lift in shaft (Source: www.mitsubishielevator.com)

Apart from car size, opening size is also important to facilitate loading and unloading of passenger. For example, opening width of 800mm is recommended for 8P lift with car size of 1400mm width × 1050mm depth which would allow simultaneous access of two passengers into lift, but would not be suitable for 13P lift with car size of 1600mm width × 1350mm depth that need to facilitate simultaneous access of three passengers into lift with condition that one passenger may need to slightly turn his body a bit.

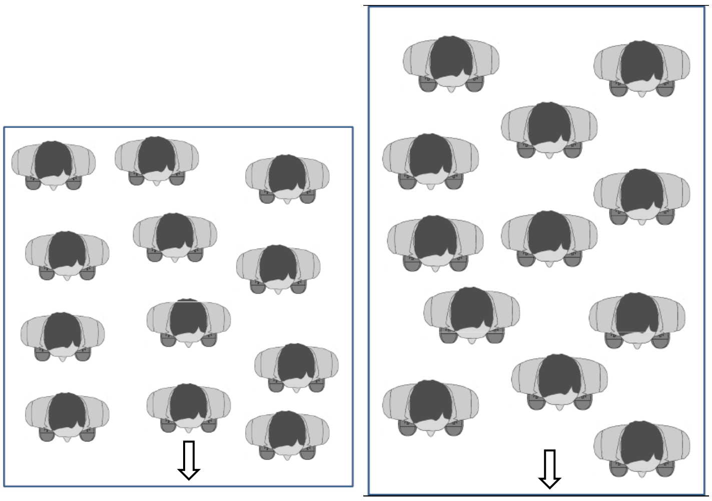


Figure 9. Illustration of distribution of passenger in square lift (1600mm width ×1550mm depth) vs stretcher lift (1300mm width × 1900mm depth), capacity is 15 persons with 80% loading, opening size of door is center opening 900mm width × 2100mm depth, arrow shows exit door from lift.

Car size of lift shall also comply with duty table stipulated in FMA, common car size vs capacity being industry standard is illustrated in Table 2. The original table uses square feet and lbs, hence, the converted meter square and kg table is used. Due to irregular figures as a result of lbs to kg conversion, lift manufacturers will round them up for convenience of designer and users, this figure might be slightly different among manufacturers.

Table 2. Common car size vs capacity comply with FMA.

Area (ft^2)	Area (m^2)	Min Area (m^2)	Max Area (m^2)	Person	Mass (lbs)	Mass (kg)	Recommended Capacity (kg)
12	1.11	1.06	1.16	6	900	408.23	415
15.6	1.45	1.4	1.5	8	1200	544.31	545
17.2	1.6	1.55	1.65	9	1350	612.35	615
18.9	1.76	1.71	1.81	10	1500	680.39	685
20.4	1.9	1.85	1.95	11	1650	748.43	750
23.6	2.19	2.14	2.24	13	1950	884.5	885
26.7	2.48	2.43	2.53	15	2250	1020.58	1025

29.5	2.74	2.69	2.79	17	2550	1156.66	1165
35	3.25	3.2	3.3	21	3150	1428.81	1430
38.8	3.6	3.55	3.65	24	3600	1632.93	1635
47.3	4.39	4.34	4.44	30	4500	2041.16	2045

In some cases, constraints of lift shaft apply mostly due to space limitation of building. There is no fixed approach to design layout of lift, it varies from manufacturer to manufacturer. Some manufacturers design lift with counterweight located at the back of lift car (back drop), and some manufacturers design lift with counterweight located at the side of lift car (side drop). It depends on width of total width and depth of lift car, type of opening e.g. center opening or side opening, with of counterweight and roping arrangement. For a shaft with narrow width, common approach is to design stretcher lift with side opening so that appropriate opening width could be kept. Practical example, client will like to have 15P lift to be installed for a shaft of 1900mm width × 2000mm depth. Step 1 is to evaluate possibility of supplying standard 15P lift 1600mm width × 1550mm depth:-
distance from shaft wall to landing sill = 80mm
running clearance (R.C.)= 30mm
depth of car sill = 60mm
depth of front return panel = 90mm
car depth = 1550mm
thickness of car wall = 30mm
clearance between car wall and counterweight = 50mm
thickness of counterweight = 150mm
minimum clearance between counterweight and shaft wall = 50mm
summation of the above gives 2090mm > 2000mm, therefore the next lower capacity 13P lift with depth of 1350mm shall be proposed. Step 2 is to evaluate possibility of supplying standard 13P lift 1600mm width × 1350mm depth, center opening 900mm:-
total width of CO 900 car door operator = 1860mm , hence clearance between car door operator at both sides will be (1900 - 1860) × 1/2 = 20mm < 50mm minimum clearance between moving car operator and shaft wall, therefore shaft width could not accommodate CO900 opening.
total car width = car width + 2 × thickness of car wall = 1600 + 2 × 30 = 1660mm
distance between guide rails (D.B.G.) = total car width + 2 × car frame to guide rail distance = 1660 + 2 × 45 = 1750mm
height of guide rail (13K guide rail) = 69mm
Minimum size of bracket including 3mm shim plates for vertical alignment= 78mm
summation of above = 1750 + 2 × 69 + 2 × 78 = 2044mm > 1900mm
therefore, consider next smaller capacity lift 11P with 1400mm width × 1350mm depth, CO800 opening. For CO800, total car door operator width is 1660mm, therefore clearance between car door operator and shaft wall is 120mm, this is acceptable. Total car width now become 1460, distance between guide rail = 1460 + 2 × 45 = 1550mm, hence, bracket size = (1900 - 1550 - 2 × 69) × 1/2 = 106mm, this is acceptable.

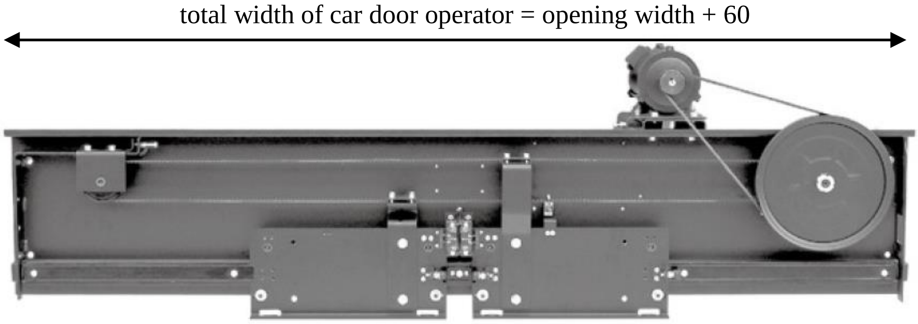


Figure 10. Typical example of car door operator for center opening. (Source: www.nbsldt.com)

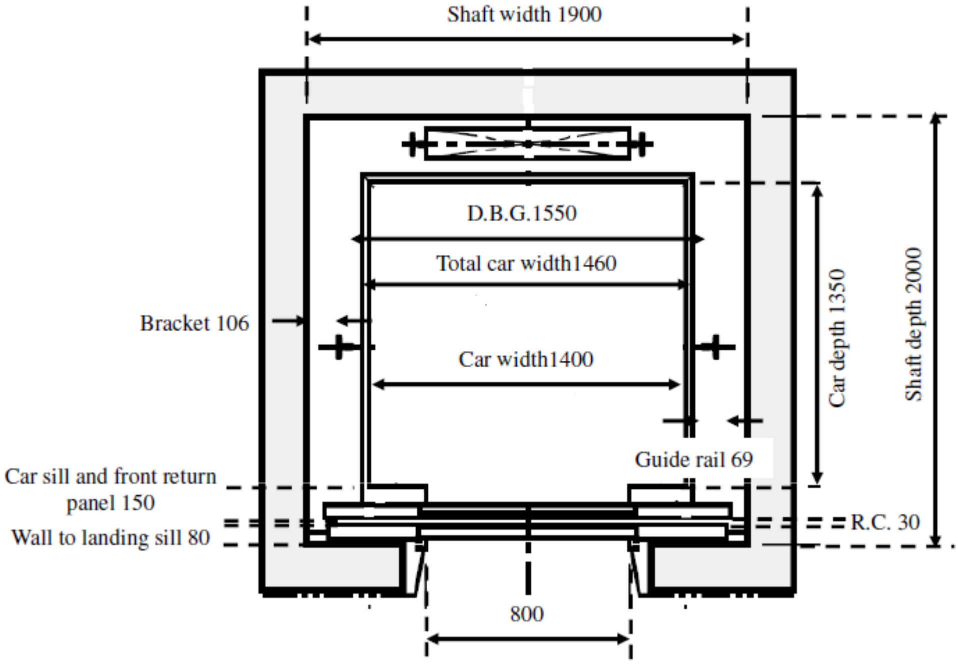


Figure 11. Final layout of 11P lift 1400mm width × 1350mm depth accommodated in shaft 1900mm width × 2000mm depth

Finally, 11P lift will be recommended to client. Total width of car door operator and final layout are depicted in Figures 10 and 11.

For all projects secured, Engineering will design lift and select appropriate equipment and components. This would be stipulated in BOM, usually there are mechanical BOM and electrical BOM. Traction machine is the important equipment for lift, therefore, it is important to select the right traction machine. There are geared and gearless traction machines used to drive lifts as shown in Figure 12. It is increasing trend that conventional geared traction machine with induction motor (IM) is replaced by gearless traction machine with permanent magnet synchronous motor (PMSM). Main advantages of PMSM are high efficiency, require no lubrication and low noise. Power in kW required for traction machine is

$$P_{machine} = \frac{\mu \times L \times v}{\eta \times 6120} \quad (9)$$

where μ is balancing factor of counterweight, typically 0.45 to 0.5, L is contract load, v is lift speed in m/min, η is efficiency of machine. For geared traction machine, η could be 0.5-0.6, meanwhile for gearless traction machine with PMSM, η could be 0.9. From Equation (9), $\eta \uparrow \rightarrow P_{machine} \downarrow$, therefore power consumption of lift could be significantly reduced. Gearless traction machine normal have smaller shaft load compared with geared traction machine. Therefore, 1:1 roping is often applied to lift with geared traction machine meanwhile 2:1 roping will be applied to lift with gearless traction machine. In some occasions, 2:1 roping is also used for lift with geared traction machine, example goods lift. Practical example, suppose that is a 2000kg goods lift with speed of 60m/min, it would not be many options for traction machine, besides that, traction machine that could support this load and speed could be too expensive. Figure 13 illustrates 1:1 and 2:1 roping configuration, load of lift will be shared by shaft of traction machine and rope terminal, where W and w are weight of lift car and counterweight respectively. Therefore with 2:1 roping, the same traction machine could take double of contract load, however, speed of lift would be half of machine (Janovsky, 1993). As such, traction machine with capacity of 1000kg and speed of 120m/min could be applied provided shaft load could withstand half of total car load and capacity with safety factor of 2. The size of inverter drive will follow motor size.

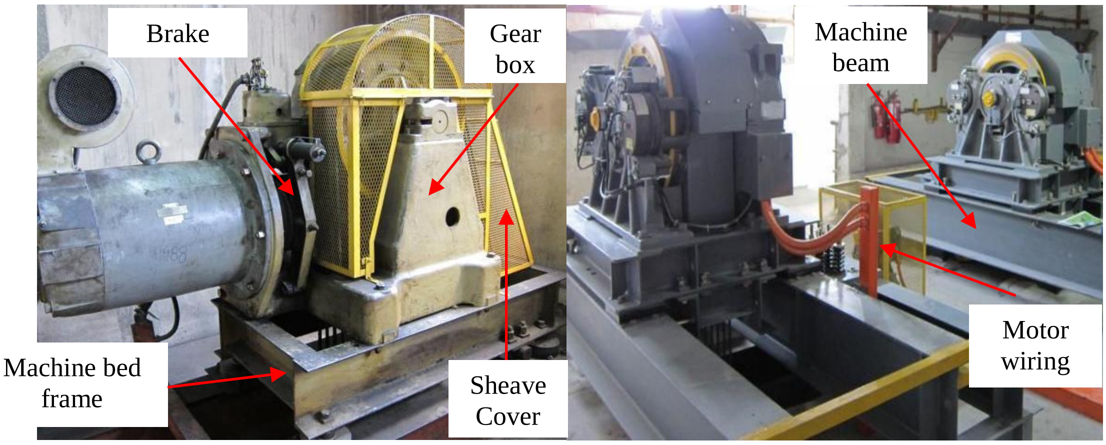


Figure 12. Geared traction machine (left) and gearless traction machine (right) at machine room

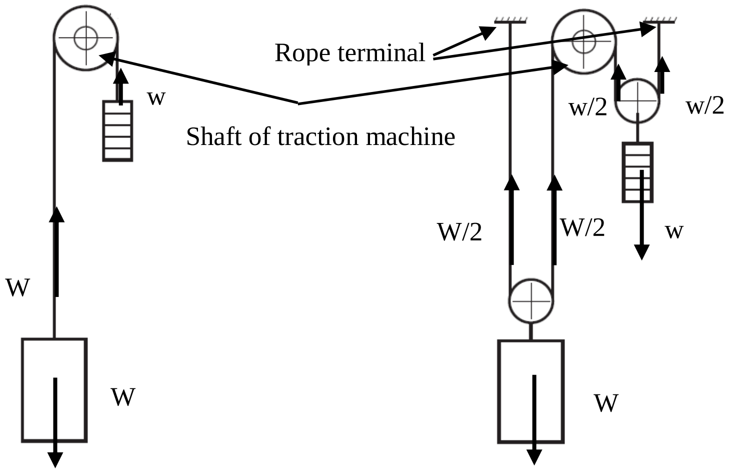


Figure 13. 1: 1 and 2:1 roping configuration of lift.

Ropes connect lift car and counterweight, movement of ropes is a result of traction generated between rope and groove of traction sheave. The minimum number of ropes is 3 irrespective of lift capacity. Common rope sizes are diameter 10mm, 12mm and 16mm. Safety factor of rope could be determined by Equation (10)

$$Safety\ factor = \frac{Number\ of\ ropes \times roping\ factor \times Breaking\ Strengh}{Total\ weight\ of\ lift\ at\ full\ load} \quad (10)$$

In FMA, safety factor of rope is at least 12. Breaking strength of rope could be obtained from test report provided by manufacturer for each drum purchased. Breaking strength is proportional to rope diameter. Practical example, consider 11P lift, total weight is 17kN, from traction machine catalogue, 4 lengths of 12mm rope to be applied, roping configuration is 1:1, breaking strength of grade E 12mm 8 × 19S Tokyo rope is 58.5kN, from Equation (10), safety factor is 13.77 ≥ 12, therefore is acceptable. Construction of 8 strand wire rope and method to measure rope diameter is shown in Figure 14.

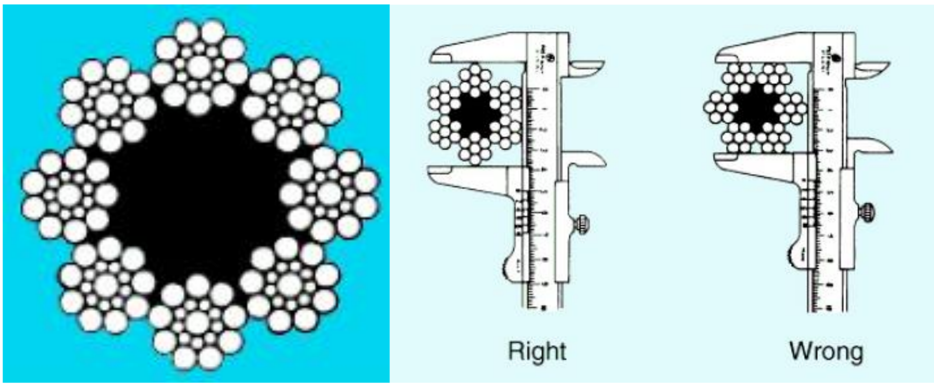


Figure 14. 8 × 19S rope used for lift application and method to measure rope diameter (Source: www.tokyorope.co.jp)

Conclusion

In this paper, it is learned that lift technology is not something new and engineers have made effort since 1920s to lay strong foundation that lead to modern lift today. Typical business process of lift industry is discussed to provide high level overview how different stakeholders in lift company work so that lift could be put into operation. Traffic requirement is also being discussed to provide brief understanding of factors to be considered during early design stage. Lift system design is also being discussed to provide fundamental understanding of layout design, machine sizing, roping configuration and safety factor of ropes. As there is not much literature related lift in Malaysia, hopefully this paper will inspire more writings by local engineers about lift in Malaysia context.

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