Quantifying Maintainability Parameters for Vertical Transport System

Chew M.Y.L.[1]
Sutapa Das [2]
Nur H.B. Sulaiman [3]

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ABSTRACT

Elevators or lifts form the vertical transportation spine of modern high rise buildings. Safety and convenience being two critical issues, it is important to identify the associated risk factors. To complement the technological advancements of system design and greater users' expectation, there is a noted absence of maintainability aspect which not only ensures efficient system performance but also lowers the total life cycle cost through smooth operation and minimal maintenance. To address this knowledge gap, this research was undertaken to identify, analyse and quantify serious defects prevalent in the vertical transport system of commercial buildings of Singapore.

From detailed case study at five commercial buildings, total 114 types of common defects were identified for five main components including machine room, car, hoistway, landing and pit. Out of them, 28 were graded as significant by 40 experienced facility managers in a five pomt Likert scale in terms of frequency of occurrence, and adverse effect on: economy, system performance and safety & comfort. Comprehensive defect analysis established that inadequate or careless maintenance was the main cause for most of them. This study provides foresight of the long term effect of the decisions made during design, construction and operation-maintenance stage and forms the basis of good practices for efficient and safe functioning of highly maintainable vertical transport system. This generic method is applicable for any other building services.

KEYWORDS

Defect Analysis, Life Cycle Cost, Maintainability, System Performance, Vertical Transport

[1] National University of Singapore, School of Design and Environment, Singapore 117566, Phone +65 6516 3496, Fax +65 6775 5502, bdgchewm@nus.edu.sg
[2] National University of Singapore, School of Design and Environment, Singapore 117566, Phone +65 8112 5061, Fax +65 6775 5502, sutapa@nus.edu.sg / sutapa.d@gmail.com
[3] National University of Singapore, School of Design and Environment, Singapore 117566, Phone +65 9644 4215, Fax +65 6775 5502, nhsulaiman@gmail.com

1 INTRODUCTION

Elevators or lifts form the vertical transportation spine of modern high rise buildings. Since the invention of safety gear by Elisha Otis in 1953, elevators have undergone significant improvement especially in related areas such as: traffic handling, control systems, traction systems and vibration dampers. As modern elevators are complex equipment designed, produced and installed under stringent regulations, they are inherently safe. However in spite of a safety factor as high as 16, ISO certification of most of the manufacturers / installers, elevators and escalators related accidents kill about 30 and seriously injure about 17,100 people each year alone in the United States and 50% of the victims are trained elevator mechanics [McCann 2004].

Safety rules [ISO 2004] are focused at various types of accidents with lifts: shearing, crushing, falling, impact, trapping, fire, electric shock, damaged material, accidents due to wear or corrosion (Staal & Quackenbush 1998). Among the prevalent problems such as over speeding of car, uncontrolled low speed, car moving before door is closed etc, the most common hazard is fatal fall through elevator shaft due to opening of lobby door on pressing of call button before the car arrives [Vlahovic 1990]. Moreover equipment shutdown incurs in expensive over time 'callbacks' and inconvenience to the users. Such malfunctioning can be prevented by efficient maintenance practices [NEII 2007].

In spite of regular inspection according to elevator maintenance checklists [Schloss 1998], defects are prevalent. From extensive literature review it was established that to complement the technological advancements of system design and greater users' expectation, there is clear need for a better understanding of maintainability aspect to ensures efficient system performance and lower total life cycle cost through smooth operation and minimal break-down. Causes and long term effects of defects need to be addressed explicitly in design guidelines and maintenance handbooks. This research was undertaken to identify the defects common in the vertical transport system in commercial buildings of Singapore and to rank the significant one based on the scientific quantification of their seriousness. This study focuses on traction type passenger elevators generally found in high-rise commercial buildings.

2 RESEARCH METHODOLOGY

2.1 Data Collection

In order to obtain a preliminary idea of common maintenance problems in vertical transport system, major components were listed from available literature for a systematic site investigation. In the first phase of data collection, an in-depth field survey was conducted in five commercial towers. Discussion with facility managers (FM) and maintenance personnel was followed by expert walk-through and photo documentation of all permissible areas to investigate elements such as the machine room, car interior etc. The defects were analyzed with the help of information provided by FMs, past maintenance records of the buildings under study and the knowledge gained through the literature review [McKain 1999; O'Donoghue & Jarboe 2007; SAC 2000; Strakosch 1986] were elicited.

From preliminary analysis, a defect was observed to have adverse effect on (1) economy, (2) system performance; and (3) safety & comfort. These factors contribute to the level of seriousness of a defect and were considered to establish the significance of a defect. A frequent defect might have insignificant effect, while a very serious defect may occur rarely. For example, closing of car door while user are getting in and out of the car is common but the force exerted causes only nudging effect, while false opening of a lobby door when there was no elevator car is rare but can cause fatal fall through hoistway. The three major impacts were defined as:

- Economic loss: considerable financial damages sustained as a result of the defect, e.g. call back if users are caught in a stalled car due to deactivated safety switches or faulty circuits.

- System performance loss: here the system performs significantly below normal operating efficiency due to the defect, e.g. repeated opening and closing of car door.
- Safety & comfort loss: affected safety of the users and maintenance personnel as a result of the defect, e.g. opening of fire lift car door in fire floor if the lobby smoke detector is faulty.

The defect data related to major components and sub-components of vertical transportation system was collated in a detailed survey questionnaire. In a face to face interview, 40 experienced facility managers (FM) were asked to indicate the frequency of the defect in a five point Likert scale, where, 1 = 'rare', 2 = 'sometimes', 3 = 'quite often', 4 = 'very often' and 5 = 'always'. In order to estimate the impact of each defect, the respondents were asked to indicate the significance of the defects in terms three consequences also in a five point Likert scale, where, 1 = 'Nil', 2= 'Slight', 3 = 'Moderate', 4 = 'Serious' and 5= 'Very serious / fatal'. Among five major components, the questionnaire for elevator hoistway is shown in Appendix A as an example.

2.2 Data Analysis

Mean ratings for determining the level of seriousness of the defects were calculated from the feedback received. Mean rating for frequency was defined as $\overline{X}_{FR}$, while the same for impacts on four aspects, namely, economy, system performance, and safety & comfort were denoted by $\overline{X}_{EC}$, $\overline{X}_{SP}$ and $\overline{X}_{SC}$ respectively. For each defect, the mean rating was calculated by a general formula (Equation 1). Using statistical tool SPSS 12 (Statistical Package for the Social Sciences), T-test was carried out to identify the significance of each mean. The midpoint test value of 3 (by definition) was assigned to measure whether the defects have a significantly large enough mean with p<0.005.

$$\text{Mean frequency of occurrence } \overline{X} = \sum_{l=1}^{5} i \times n_i \Big/ \sum_{l=1}^{5} n_i \qquad (1)$$

Where, i = frequency rating and n_i = number of responses for i-th rating

3 RESULTS AND DISCUSSION

3.1 General Observation

Most of the commercial buildings in Singapore are accessible by elevator.. Geared traction elevators are used generally up to 20 storeys, while gearless express type is common for taller buildings. Misuse and vandalism such as banging on door, repeated pressing of buttons, littering and forceful opening of lobby door were observed, in lift lobby and car interior. These are accessible to users. Most of the system related defects were attributed to poor installation quality or mishandling during maintenance which could have been prevented by cleaning and proper lubrication of machinery.. Causes of defects were grouped into: (1) design-specification (D); (2) construction-installation (C) and (3) maintenance (M).

3.2 Survey Results

The summary of survey results illustrating the prevalent defects and their significance is presented in Tables 1 – 5. A total of 114 defects related to five major components of vertical transportation system were identified, out of which 28 were found serious and among those 11 were referred by FMs as frequent and 14 occurs in two or more categories. Economy, system performance, and safety & comfort were affected by 14, 14 and 9 defects respectively. Few defects which are not significant but contribute to overall maintainability were captured by three generic categories, namely, design, construction and maintenance. As an example, defects in hoistway are discussed in details

Table 1. Significance of defects in machine room

Sub-comp.	*Defects in machine room*	*Cause*	$\overline{X}_{FR}$	$\overline{X}_{EC}$	$\overline{X}_{SP}$	$\overline{X}_{SC}$
Significant defects (7 nos.)						
Controller	(1) Lift jam (stalled car)	M		2.62	3.10	3.15
	(2) Uncomfortable motion / jerky landing	C M	2.29		2.80	3.15
	(3) Long waiting time (>30sec)	D M	2.28			
Governor Machine	(4) Vibration during travel due to governor rope worn/ uneven tension/ not strong	D M			2.90	
	(5) Intermittent fault difficult to detect`	D C M		2.65		
---------	(6) Poor workmanship. E.g. Brake rod not secured to plate / uneven	C	2.51			
---------	(7) Mishandling. E.g. under / over lubrication	M		3.08		
Other defects (30 nos.)						
Machine Room	(1) Dirty with rubbish, carbon dust, lubricant; (2) Insufficient lighting (<200 lux at floor level); (3) Water seepage through wall / ceiling; (4) Overheated (>38°C) machines in stuffy room; (5) Inadequate clearance around machines & control panel					
Controller	(6) Transformer noisy / dirty; Inverter cooling fan dirty / dusty, (7) Intermittent faults/ fire from overused/ burnt resistor, (8) Noisy bearing; (9) Dirty machine with leaking cover/ oil seal					
Traction machine	(10) Oil level is too low or high; (11) Oil level gauge blurred / faulty; (12) Faulty brake; (13) Noise and vibration by worn out, dry secondary sheave bearing/ groove; (14) Machine bed isolation rubber worn; (15) Main rope worn; (16) Carbon brush holder loose/ damaged					
Tractn. motor	(17) Bearing noisy; (18) Overheated motor, (19) Cooling fan dirty / noisy					
Brake assembly	(20) Vibration and jerky emergency stops; (21) Brake drum scratched, burnt lining; (22) Incorrect clearance of plunger stroke; (23) Brake rod is not secured to plate; (24) Brake lever uneven; (25) Brake slips excessively for emergency stop; (26) Brake shaft collar clearance out/ screw loose; (27) Levers jammed/ slippery					
Governor Machine	(28) Noisy operation; (29) Oily / dirty machine					
---------	(30 Faulty design. E.g. less clearance, long waiting					

Table 2. Significance of defects in lift hoistway

Sub-comp.	*Defects in hoistway*	*Cause*	$\overline{X}_{FR}$	$\overline{X}_{EC}$	$\overline{X}_{SP}$	$\overline{X}_{SC}$
Significant defects (7 nos.)						
Guide rail	(1) Noisy vibration due to excess movement in guide / roller shoe over slippery rail	M	2.00			
Wire rope	(2) Wrong tension in rope causes wear & tear	C M				1.82
	(3) High vibration. car hitting at top or bottom	D	1.84	2.71		2.59
	(4) Corrosion of rope	D C			2.60	
---------	(5) Faulty design. E.g. Limit switch v. close to governor rope (over conservative design)	D				2.06
---------	(6) Poor workmanship. E.g. Rope socket is slanted or with bullock-clip in the wrong position causes wrong tension in wire rope	C	2.52	2.44	2.75	
---------	(7) Mishandling. E.g. Oil spillage	M		3.08	2.74	
Other defects (6 nos.)						
Governor	(1) Updown switch roller jammed/ misaligned; (2) Limit switch & gov. rope too close					
Guide rail	(3) Separator beam, rail bracket dirty with rubbish; (4) Slippery by oil spillage					
Shaft	(5) Not covered by hatch; (6) Water seepage					

Table 3. Significance of defects in lift car

Sub-comp.	*Defects in lift car*	*Cause*	$\bar{X}_{FR}$	$\bar{X}_{EC}$	$\bar{X}_{SP}$	$\bar{X}_{SC}$
Significant defects (6 nos.)						
Car Interior	(1) Wear and tear with time: discolouration, dents, , worn flooring, worn off buttons, missing / blurred message /certificate plate	D M	4.73	3.23		
Car Door	(2) Door jam/ stuck	M		3.55	4.08	
	(3) Repeated opening and closing	M			4.17	
	(4) Incomplete opening and closing	M		3.51	3.74	
	(5) Door closing on moving users as PE eyes or multi beams not aligned to detect movement	C M				3.93
---------	(6) Design specification sensitive to vandalism. E.g. Car operating panel (COP) dirty/ delaminated/ with buttons which are loose / jammed / without light / unable to register call. Easy opening of emergency exit at top	D	4.46			
Other defects (34 nos.)						
Car Top	(1) car top rope socket wrongly placed/ slanted / hitting; (2) Misfit rope wedge; (3) Excessive movement in car guide roller shoe; (4) Safety gear/linkage oily& dirty or dry & noisy; (5) Low overhead without warning sign; (6) Dirty with debris, lubricant					
Car Bottom	(7) Overload switch / cell jammed; (9) Compensation cable not firmly secured; (10) Safety gear jammed/ missing parts/ inadequate clearance; (11) Travelling cable not firmly secured; (12) Lower surface is dirty with cobwebs; (13) Excessive movement of guide shoes / roller					
Car Interior	(14) Dirty / damaged light diffuser; (15) loose /noisy false ceiling, noisy fan; 16) Architectural finishes hindering maintenance.					
Car Door	(17) Banging; (18) Linkages worn; (19) Door shoe is worn/ inaccurate clearance / loose; (20) Door sill is bulging; (21) Speed mismatch with lobby door (time lag); (23) Door jamb loose / rusty / stopper missing; (24) Car safety shoes hitting / noisy					
Door operator	(25) Door motor is slanted or causing vibration; (26) Door motor belt tension loose / worn; (27) Door motor chain/ sprocket/ wheel is loose / worn out and dry; (28) Faulty micro switch is unable to prevent door opening within unlocking zone; (29) Faulty mechanical lock; (30) Car door bar / hanger roller is dirty/ worn / rusty					
Travelling	(31) Lift levelling with landing > 5mm; (32) Jerk, vibration, noise					
---------	(33) Poor workmanship. E.g. Loosely fitted false ceiling					
---------	(34) Mishandling. E.g. damaged micro switch.					

Table 4. Significance of defects in lift pit

Sub-comp.	*Defects in pit*	*Cause*	$\bar{X}_{FR}$	$\bar{X}_{EC}$	$\bar{X}_{SP}$	$\bar{X}_{SC}$
Significant defects (3 nos.)						
----	(1) Dirty with rubbish or lubricant	M	3.42		3.10	3.40
	(2) Compensation cable/ sheaves misaligned	D C		2.84		3.43
	(3) Noisy compensation cable	M	1.62	2.75	2.79	
Other defects (1 no.)						
----	(1) Damaged switch / light					

Table 5. Significance of defects in lift landing

Sub-comp.	*Defects in landing*	*Cause*	$\overline{X}_{FR}$	$\overline{X}_{EC}$	$\overline{X}_{SP}$	$\overline{X}_{SC}$
Significant defects (5 nos.)						
Landing door	(1) Rubbing/ large gap (> 10mm) in panel	D C M			3.28	3.68
	(2) Catch device roller worn/ hitting/clearance out	D M		2.78		
Lift Landing	(3) Hall button damaged/ no light/ loose/ jam	D M	4.18	3.08		
---------	(4) Poor workmanship. E.g. misaligned door roller wears easily	C			2.75	
---------	(5) Mishandling. E.g. jammed mechanic's access switch by forceful use of other key	M		3.08	2.74	
Other defects (8 nos.)						
Landing door	(1) Closing on moving users / no self-closing; (2) Door roller worn/ rusty/ clearance out/jammed; (3) Weight wire pipe damaged/ missing/ loose; (4) Lock contact worn / clearance out; (5) Shoe worn / clearance out; (6) Missing /damaged rubber stopper					
Smoke detector	(7) Missing/ damaged detector unable to stop lift reaching the fire floor					
---------	(8) Faulty design. E.g. Sensitive finishes used in lobby with heavy use, inferior make of lock, clutch shoe wear off easily					

3.3 Discussion

For four sub-components of hoistway, a total of 13 common defects were identified from the first phase of data collection, among which seven were found to be significant for their impacts (Table 2). Excessive noise and vibration in guide rail during lift travel was found to be a frequent issue due to excess movement in guide or roller shoe. Careless maintenance is not only responsible for oil spillage during lubrication but also for wrong size of roller shoe. As mentioned earlier, elevators are manufactured under stringent ISO certification, it can be realized that misfit shoe is a result of replacement, not a manufacturing defect. This same logic is equally applicable to misaligned socket or improper wedge size causing wrong tension in rope. Overloading can be considered as an example of misuse rather than inadequate design consideration in this case. Vibration in hoisting rope was reported to occur quite often, but more than being frequent it has major implication on economy and comfort. The distress caused to users actually results in complaints and costly callbacks. Ropes get corroded due to undue stress and water seepage through hoistway. Both have the root cause of poor workmanship either during installation of lift or construction of lift shaft. All of these four significant defects mentioned had poor workmanship as common cause. This fact was further illustrated by the fact that it was graded as the most frequent defect. It is in agreement with the general understanding that quality control at site is not as strict as of factory. As a result the systems performance is highly affected since commissioning incurring higher maintenance cost. Limit switch too close to governor rope was an example of over conservative design. It creates uncomfortable emergency stops. Wrong maintenance practices such as oil spillage during lubrication or misalignment of machine parts was observed to affect system performance seriously, and have highest impact on cost.

From the present study, it was established that among many defects in vertical transport system, most of the defects can be prevented by considering three major maintainability criteria, namely, design and specification, construction or installation, and operation & maintenance (O&M). Few defects may have more than one cause. It is important to know at which stage what are the defects arise so that the appropriate preventive measures can be taken to improve the maintainability. It was found that among 28 significant defects, 12 were design related, 10 were due to faulty installation or poor construction quality and inadequate O&M practises were responsible for 19 defects. The maintenance quality was largely subjective with regard to cleanliness and lubrication.

3 CONCLUSIONS

The study had identified 28 persistent defects out of total 114 defects commonly occurring in five major components of vertical transportation system. Mishandling of components during regular maintenance including improper lubrication and inadequate cleaning was detected as the most common cause for majority of the defects. From the analysis based on feedback provided by 40 experienced FMs regarding: (1) frequency of occurrence of various defects and (2) seriousness of the defects in terms of their adverse effect on economy, system performance and users' safety & comfort, it was established that the most important contributing factors for maintainability is good maintenance, next comes good design and material specification, followed by workmanship during construction or installation. This comprehensive defect analysis was aimed to help the designers, contractors and facility managers to realize the long term effect of their decisions made and form the basis of an enhanced maintainability to promote good practices for efficient and safe functioning of highly maintainable vertical transportation system. Further, this may provide a simple guideline for FM to achieve and as well as owner to enjoy lower life cycle maintenance cost of building services. This generic research method can be applicable for any other building services.

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APPENDIX A: Sample questionnaire for defects in hoistway

DEFECTS FOR ELEVATOR HOISTWAY			**Grading for Frequency**	**Grading for Impacts**		
Sub-component	**Description of defect**	**Probable Causes of the Defect**	**1= Rare 2= Sometimes 3= Quite often 4= Very often 5= Always**	**1=Nil 2= Slight 3=Moderate 4=Serious 5=Very serious**		
				Econ	**Sys**	**Sfty.**
Governor	Up-down switch roller jammed/ worn/ misaligned [M]	−Intermittent fault due to circuit breaks −Dust / dirt deposit into the hoist way				
	Limit switch too close to governor rope [D]	−Wrong selection of design factor				
Guide rail	Noisy vibration due to excess movement in guide / roller shoe [M]	−Guide / roller shoe of the wrong size −Slippery rail due to oil spillage during lubrication				
	Separator beam, rail bracket dirty with rubbish [M]	−Vandalism (rubbish thrown by users) −No cleaning after regular maintenance				
	Slippery by oil spillage [M]	−Careless lubrication				
Shaft	Not covered by hatch [M]	−Removal of cover during careless maintenance				
	Water seepage [C]	−Poor workmanship of building structure				
Hoisting rope	Excessive vibration / car hitting at top or bottom [D]	−Overloading of car −Wrong tension in rope if 3-fold instead of 4-folds				
	Wrong tension in wire rope causes wear & tear [C, M]	−Overloading of car −Rope socket is slanted / hitting / socket bullock-clip is in the wrong position −Wedge of wrong size				
	Corrosion of rope [D, C]	−Stress corrosion, hoistway not dry,				
-----	Design defects [D]	−Faulty design or poor specification				
-----	Construction defects [C]	−Poor workmanship during installation				
-----	Maintenance defects [M]	−Mishandling during careless maintenance				

[D] Defect caused by poor design or material specification
[C] Defect caused by poor workmanship during construction / installation
[M] Defect caused by inadequate or careless maintenance