System Strategies in the Management of Transit Systems towards the End of Their Life Cycle

By

Ajmer Singh Kairon
CEng, Eur Ing, MIMechE

BEng Mechanical Engineering (Hons) (1994)
University of Leicester, United Kingdom

MSc (Eng) Railway Systems Engineering (1999)
University of Sheffield, United Kingdom

Submitted to the System Design and Management Program
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Management and Engineering

At the

Massachusetts Institute of Technology
[February 2007]
December 2006

Signature of Author ______________________________
System Design and Management Program
December 20, 2006

Certified by ______________________________
Nigel H. M. Wilson
Professor of Civil and Environmental Engineering
Thesis Supervisor

Certified by ______________________________
Patrick Hale
Director
System Design & Management Program

System Strategies in the Management of Transit Systems towards the End of Their Life Cycle

By

Ajmer Singh Kairon

Submitted to the System Design and Management Program
on December 20, 2006 in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Engineering and Management

ABSTRACT

This thesis explores and evaluates essential strategies needed for the transit authority/operator to deal with end of life cycle challenges of Rapid Transit Systems (RTS) systems. RTS systems are elaborate systems consisting of various subsystems. It is believed that one of the greatest challenges of such systems is the integration of these various sub-systems to ensure that they work correctly; functionally and safely at the onset of development. While this is true there also exist real challenges towards the end of the life cycle which unfortunately is not dealt with during the design conceptualization and implementation.

The fact that the RTS system is an elaborate amalgamation of other subsystems functioning together makes the management of its end of life cycle challenging. The life spans of these various subsystems are different i.e. the mismatch in life cycles of these systems could cause serious problems in the future. There are two approaches to manage these challenges i.e. look at it from a design standpoint and start incorporating fixes at the design stage to address end of life cycle challenges (start of the value chain) or look at the already present RTS systems around the world and see what can be done when most of the systems are mid life or nearing end of life and formulate strategies to address these challenges (end of the value chain). This thesis has focused on the latter approach given that systems at mid-life and near end of life are of priority now and further any lessons learnt from these exercises could be incorporated into new designs.

Four different strategies were defined and assessed: Public Private Partnerships (PPP), reusability/remanufacturing/ recycling, life extension and leasing. In planning of the end of life cycle challenges it must be acknowledged that no one strategy is always best. The strategies at most allow the transit authority/operator to make more meaningful and informed decisions based on risk and cost amongst many other factors. This allows a transit authority/operator to plan ahead. The transit authority/operator should look at their RTS system and evaluate the best strategy. It may be the case that one of these strategies meets their needs or a hybrid of these strategies

Thesis Supervisor: Nigel H. M. Wilson

Title: Professor of Civil and Environmental Engineering

Acknowledgements

It has always been a dream to come to this premier and world class institution to educate and enrich myself. My motivation of coming to MIT on the System Design and Management program was to forge my own style of management and to learn from the best. It is atypical in the Singapore Civil Service to be paired up with a senior member of staff to learn from. While this helps one develop it also allows one to assimilate shortcomings as well. The biggest hurdle of coming to MIT was affordability but I persevered and with the support of my wife, Lillian, I sought out organizations that were willing to support me. Thus together with the Fulbright Commission, Bombardier Transportation and the group of three executors of the "Estate of Jacob Ballas", Ms. Norma Phyllis, Mr. Frank Benjamin and Mr. Joseph Grimberg I was able to pursue my dream. To all of these organizations, I am deeply indebted. Armed with their support and my life savings, I arrived in Boston in the pursuit of my dream and after all what are dreams if not to come true.

I am very grateful to my thesis supervisor Prof. Nigel H M Wilson for his guidance and advice. I really enjoyed Prof. Wilson's classes and the constructive conversations we have had. My interactions with Prof. Wilson have been an educational experience in their own right and exemplify my objective of learning from the best. Special thanks also go to Mr. John Attanucci for his comments on my thesis write-up and Ginny for the administrative support.

I would like to thank Mr. Patrick Hale, the SDM course director for his guidance throughout my SDM experience here at MIT. Pat was very instrumental in seeking out financial support for me to pursue this course and went out of his way to help. The other staff in the SDM office John, Ted, Chris, Bill and Taya has been very helpful this past year. For this, I am truly grateful!

I would also like to thank Mr. Ray Betler, President, Total Transit Systems and Mr. TC Chew, President, London Underground Projects of Bombardier Transportation who have kindly supported my thesis work. Bombardier has gone out of their way in providing me with the materials that I requested and arranging for a study trip to their plant in Pittsburgh. My interaction with these industry experts have helped substantially in my work. Also thanks go to the LTA for the production of some of their material.

Finally I would like to thank my family, in particular my wife Lillian for always believing in me and being very supportive through this one year here at Boston and single handedly taking care of my two young sons Ryan and Ray.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AFC : Automated Fare Control
ATC : Automatic Train Control
ATO : Automatic Train Operation
ATP : Automatic Train Protection
APM : Automated People Mover
BCE : Brake Control Electronics
CBM : Condition Based Maintenance
CM : Corrective Maintenance
CSC : Contactless Smart Cards
CSS : Concept Safety Submission
CTRL : Channel Tunnel Rail Link
DFE : Design for the Environment
DSS : Design Safety Submission
E&M : Electrical and Mechanical
EIFS : Enhanced Integrated Fare System
EMC/EMI : Electromagnetic Compatibility and Interference
EPBM : Earth Pressure Balancing Machine
HC : Historical Cost
IGBT : Insulated Gate Bipolar Transistor
ISCS : Integrated Supervisory Control System
LCD : Liquid Crystal Display
LCTP : Lowest Compliant Tender Price
LUL : London Underground Limited
LTA : Land Transport Authority
NFPA : National Fire Prevention Authority
MBTA : Massachusetts Bay Transportation Authority
MFV : Multi-Function Vehicle
MRP : Master Replacement Plan
NATM : New Austrian Tunneling Method
OCC : Operations Control Centre
OSS : Operations Safety Submission
PCE : Propulsion Control Electronics
PDS : Power Distribution System
PFI : Private Finance Initiative

PM : Preventive Maintenance
PPP : Public Private Partnership
PSD : Platform Screen Doors
PSR : Project Safety Review
RATIS : Real Time Transit Information System
RCM : Reliability Centered Maintenance
RGV : Rail Grinding Vehicle
RoHS : Restriction of Hazardous Substances Act
RP : Replacement Plan
RTS : Rapid Transit System
RSS : Rehabilitation/Replacement Safety Submission
TBM : Time Based Maintenance
TBM : Tunnel Boring Machine
SCADA : Supervisory Control and Data Acquisition
UPS : Uninterrupted Power Supply
VCC : Vehicle Control Center
VFM : Value For Money
VPIS : Visual Passenger Information System
WIN : Waveguide Information Network

Chapter 1: Introduction

Rapid Transit Systems (RTS) are evolving rapidly in the world given their ability to transport large volumes of passengers quickly and efficiently. As their benefits become apparent, developing countries are investing large sums of money to implement these systems. However, these systems age and deteriorate in performance over their life cycle and decades after their implementation they may require renewal or replacement.

This thesis explores and evaluates strategies that a transit authority could take to deal with the aging and deterioration of these systems. It explains the technological complexities associated with RTS systems, defines what future potential challenges transit authorities may face and develops strategies to deal with these challenges.

1.1 The Benefits of Transit Systems

There is no doubt that one of the most important elements of a modern city is its transportation system. If this system is efficient and provides seamless connections for commuters throughout the city it provides for the growth of the city. To this end the transportation system is one of the governing factors in the city infrastructure. The transportation system directly influences the city's economic strength and social vitality as it facilitates access to jobs and many other activities.

In the larger cities, rapid transit systems play a vital role in the overall transportation system. The benefits of rapid transit systems are self evident. There are clear efficiency and environmental benefits to be derived from transferring urban travelers from private cars to public transport and rapid transit systems can provide the high capacities and high levels of service quality needed to sustain high density central business districts. Many cities when faced with the threat of ever-increasing traffic with the associated pollution and congestion have adopted policies and strategies to encourage this shift. Rapid transit systems, with their far greater capacity for moving people quickly and efficiently, can also effectively support urban development policies and programs[1].

---

[1] Fourace P. & Dunkerley C., Mass Rapid Transit Systems for Cities in the Developing World, Transport Review, 2003, Vol. 23, pp299-310

Other possible benefits of rapid transit systems are population and employment densification in the vicinity of transit stations resulting from the access advantage provided to these areas. Densification is considered socially beneficial because it increases transit patronage, curbs urban sprawl, generates higher tax revenues for fiscally stressed central cities and expands the opportunities for people who are transit dependent[2].

Rapid transit systems were first introduced in the late 1800's and the 1900's have seen a boom of such systems in developed countries. Table 1-1 lists a few of the existing systems in developing countries.

City	Year in Service	No. of lines	Passengers carried (millions/year)		Daily passengers per transit corridor (thousands)
			Total	Per route km	
Buenos Aires	1913	6	242	5.1	112
Bangkok	2004	2	90	3.8	125
Caracas	1983	4	403	8.8	373
Hong Kong	1979	8	792	9.0	367
Mexico	1969	11	1433	7.1	362
Santiago	1975	5	208	5.1	192
Singapore	1987	2	296	3.6	411

Table 1-1: Output of some existing mass transit systems [3]

1.2 Planning and Implementing a Rapid Transit System

To implement a rapid transit system requires a great deal of resources. A typical cost for the construction and implementation of a 40km line with a maintenance facility is approximately US$ 3.2 billion dollars and takes 5 years to fully commission an operational line[4].

A vast amount of effort in planning rapid transit systems occurs in the early stages of development and implementation. Some of these tasks include:

- Coordination with metropolitan, urban, and rural public transportation stakeholders on proposed alignments;

---

[2] Bollinger, C.R. & Ihlandfeldt, K.R, The Impact of Rapid Rail Transit on Economic Development, Journal of Economics, (42), 1997

[3] Fourace P. & Dunkerley C., Mass Rapid Transit Systems for Cities in the Developing World, Transport Review, 2003, Vol. 23, pp299-310. & http://urbanrail.net

[4] Based on the Singapore North East Line – Launched into revenue service on 20 June 2003

- Studies on travel demand forecasts, service planning, community consensus building, market analysis and land takings;
- Modeling of line characteristics and determining key variables such as ridership, frequency, availability to decide on the technology and type of transit system to meet these needs; and
- Integration of the proposed system with existing transport systems.

Based on the scale of preparatory work required it is not surprising for the studies and funding arrangements are sought well before the construction. The first line of the Singapore Mass Rapid Transit was opened in 1987 but the preparatory work was well underway in the early 1970's.

1.3 Assessment of the Rapid Transit System Life Cycle

The system life cycle of rapid transit systems represents the various phases of conceptual and preliminary design, detail design and development, production and/or construction, product use, renewals or replacement[5]. Figure 1-1 illustrates the various phases grouped into the acquisition phase and the utilization phase. The RTS system is a system product which meets the needs of transporting commuters efficiently and seamlessly.

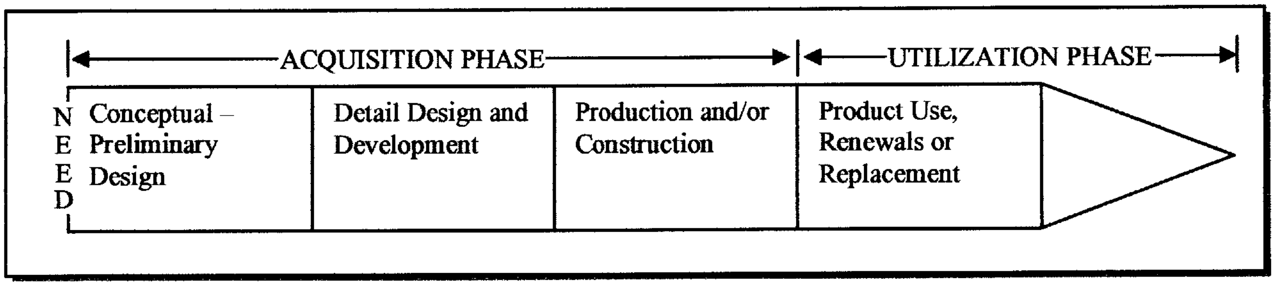


Figure 1-1: The RTS System Product Life Cycle

The RTS system is different from many other systems in the sense that it is comprised of civil, electrical and mechanical elements. A common delineator of these elements is civil and non-civil systems. The civil systems include the viaducts, the track system, tunnels while the non-civil systems include the rolling stock, signaling, communication systems for example. A detailed description of the various civil and non-civil systems will be given in Chapter 2.

---

[5] Blanchard B.S. and Fabrycky W.J., Systems Engineering and Analysis, Prentice Hall, 1998 – Diagram adapted and modified to fit the RTS system.

For RTS systems it appears that not much thought is given to the whole life cycle design and what strategies are employed towards the end of the RTS civil and non-civil life cycle. The question that is posed is why this is so? It could be that 20 to 30 years ago there was no recognition of the complexities/challenges of systems nearing their end of life cycle. Systems back then were not as complex as they are now. There is some truth to this answer. If we consider the advancements in technology for products like analog to digital video recorders, film to digital photography etc. we see that as technology advances and engineers innovate, this inevitably leads to increasing complexity in design.

Some of the literature acknowledges that companies must improve the product impact at all life cycles stages in particular the end of life cycle stage with regard to the environment[6]. The end of life cycle stage implies a product nearing the end of its usable life span as stated by the manufacturer or based on the users technical knowledge of the product. Figure 1-2 shows the various life cycle costs attributed to the various stages of a typical product life cycle. The chart assumes that all products are disposed of when they reach the end of their life cycle. However given the actual capital investment in an RTS system this approach is clearly unacceptable. While it is the norm to renew or replace elements of RTS systems when they reach the end of their life span, a complete disposal of the system is not feasible or appropriate. Thus the chart would be better adapted to an RTS system by reflecting renewals or replacement instead of system product use or disposal support.

It is acknowledged that there is nothing much that can be done to renew or replace the civil systems in particular the tunnels and viaducts in an RTS system but this thesis will still explore methods of renewing or replacing the civil systems. This is dealt with in Chapter 4.

---

[6] Rose, C.M., A New Approach to End-of-Life Design Advisor (ELDA), IEEE, 2000

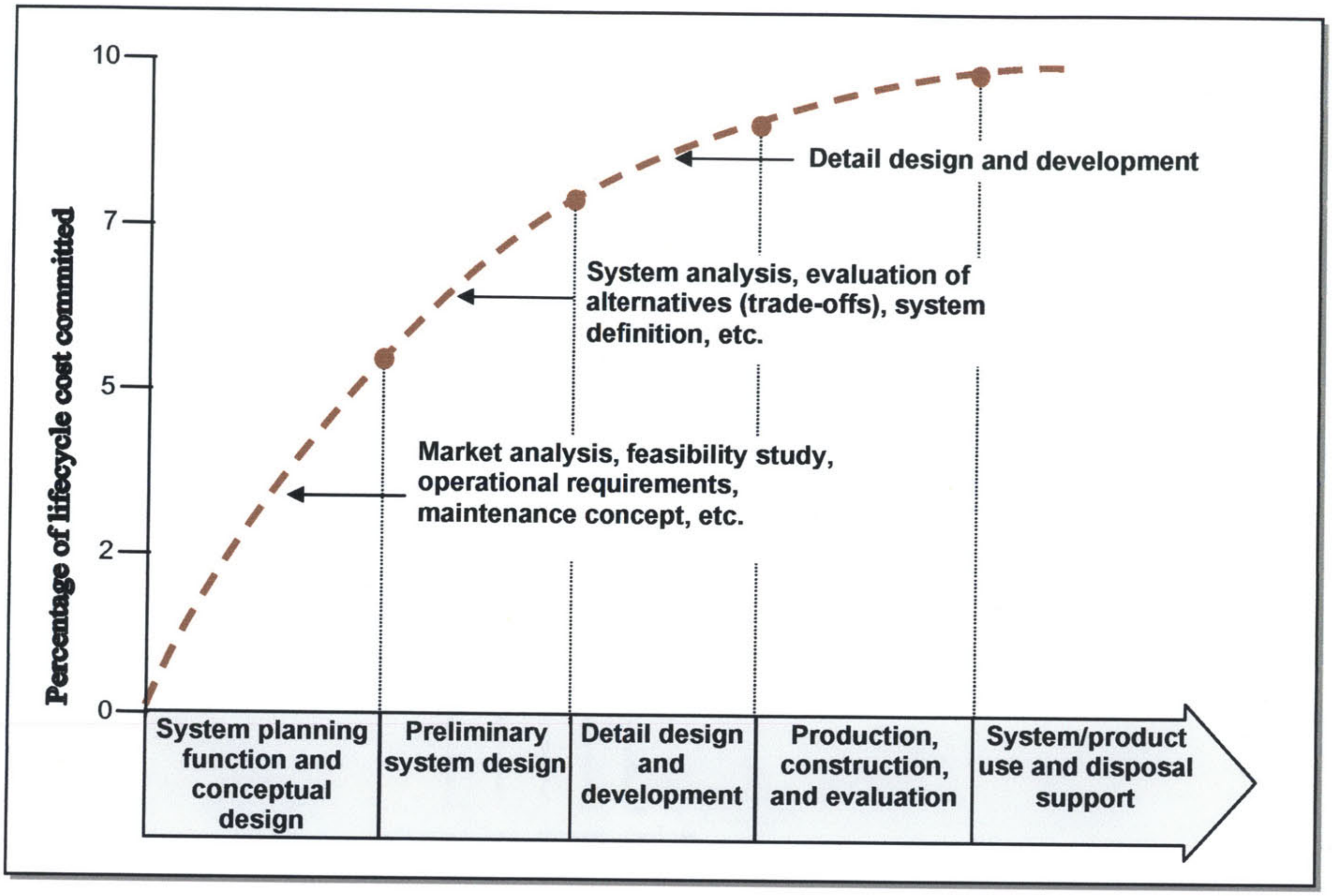


Figure 1-2: Percentage of Life Cycle Costs Committed in a Typical Product Life Cycle[7]

In this regard, reusability or life cycle extension of RTS systems becomes a significant concern. When determining if an element of the RTS system is becoming burdensome to an organization, the total cost of the RTS system over its intended life cycle needs to be considered. The maintenance and support of a legacy system[8] can consume an enormous amount of resources, in particular when the system is under increasing pressure to keep up with new technologies and component replacement[9].

Given the introduction of Insulated Gate Bipolar Transistors (IGBT) drives, moving block signaling, automated driverless systems, elaborate track fastening systems like the Pandrol double fast clip, digital communications systems etc., it would be prudent to consider

---

[7] Blanchard B.S. and Fabrycky W.J., Systems Engineering and Analysis, Prentice Hall, 1998

[8] The term *legacy system* is defined as a system reaching its obsolescence/maturity or the end of its life cycle or useful life.

[9] Blanchard B.S. and Fabrycky W.J., Systems Engineering and Analysis, Prentice Hall, 1998

strategies to deal with these systems when they reach their end of life span. In addition, designs have become more modular and scalability and functionality of a system is achieved by linking modules together. The quote below exemplifies the problem further.

> *"The time when we could think of 'legacy' as a pejorative term within the technology field is gone. As more and more or our technology efforts connect to (and integrate with) existing systems both inside and outside of our organizations, the more we must cope with legacy systems. Beyond this immediate benefit, we can develop a deeper understanding of the patterns of problems and patterns of practice that can help guide our actions even as the specifics of technologies evolve." - Jim McGee*[10]

The key point from the quote above is the notion of technology efforts connecting to (and integrating with) existing systems. Why is this important? Firstly there is a mismatch in life expectancy of civil infrastructure (120 years) and non-civil infrastructure (10, 15 or 30 years). What happens when the RTS system reaches 15 or 30 years in its life cycle? Are the non-civil systems scrapped or refurbished and if yes, how should this be done. One example is the re-signaling of the Nuremberg line in Germany[11]. The new signaling system was laid over, or superimposed on, the existing signaling infrastructure. The other benefit is that a moving block signaling system was employed and this meant less wayside signaling infrastructure needed to be laid and thus simplified the process. It should be noted though that the old signaling system was not removed and still exists as a secondary system[12].

---

[10] McGee, J, Legacy Systems : Why History Matters, esj.com, 2005

[11] Muller R., Germany's First Fully Automated Metro Status Report, UITP 78th Metro Assembly, Tehran, May 2004

[12] Information shared by Siemens Engineers, UITP Conference, Rome, June 2005

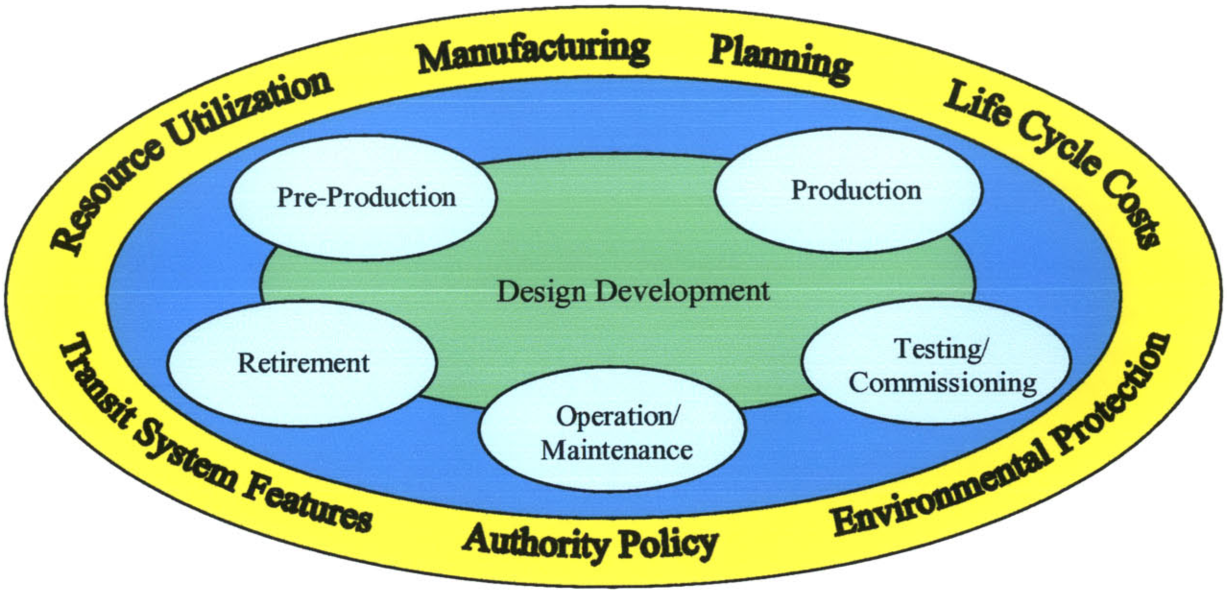


Figure 1-3: Life Cycle Planning[13]

Much of what is discussed above leads to the concept of life cycle planning as illustrated in Figure 1-3. As part of life cycle planning the retirement of the system is one component of life cycle planning. The aim of this thesis is to address this function in life cycle planning in terms of the strategies that an Operator or Authority should employ when facing the end of life cycle of RTS systems. It also highlights that the RTS system product is peculiar in its composition of civil and non-civil elements and hence complicates the life cycle planning.

Once the RTS subsystems nears its end of life cycle it could be viewed as a legacy system. Do we add on customized products or refurbish the system in its entirety? If refurbishment is done it is going to be costly and disruptive to operations. If we add on components there is a mismatch in technology and this can lead to a lot of uncertainty in technology performance. Therefore, the onus is on the Authority/Operator of such systems to realize the ramifications of ignoring the end effects and uncertainty that lies ahead towards the end of the system/technology life cycle. Manufacturers of transit systems are always developing new technologies and thus are seemingly oblivious to, or unaffected by the

---

[13] Figure adapted and modified for RTS systems from : Guidice, F. et al, Product Design for the Environment, Taylor and Francis, 2006

obsolescence of technology. Any new version of technology is revenue generation to the manufacturer and is the nature of the business.

This obvious mismatch in objectives also has social and economic consequences. If Authority/Operators develop such strategies to address the end of life cycle issues and formulate these into contracts with manufacturers, it is only then that the manufacturers would place greater emphasis on end of the life cycle challenges.

1.4 Research Motivation

In the course of my work in the Land Transport Authority in the Systems Division, the division has encountered many problems with regards to equipment obsolescence; OEM's not supporting the products they build and systems nearing the end of their life cycle.

Let us take for example, a project of implementing a Visual Passenger Information System (VPIS) on the trains in 2001. The aim of the system was to provide operational data and video entertainment to passengers on the majority of trains in Singapore. The project was to take a total of 3 years to implement and as a result of design delays the entire VPIS system was implemented and handed over to the Operator in 2005. However, by that time and as a result of poor design by the manufacturer, the Liquid Crystal Displays (LCD) developed a white patch caused by condensation. All trains in Singapore are air conditioned and because of the differences in temperature of the interior saloon of the car and the warm LCD, this created a large temperature gradient and hence caused condensation in the LCD screens. This white patch of condensation obscured the image on the LCD and thus had to be replaced. The issue then was that Fujitsu the original supplier of the LCD had sold their business to Sharp who had in turn decided to discard the 15" LCD design that had been used. Thus, in a matter of four years, one component of the VPIS system had reached obsolescence when the entire life span of the VPIS system was 10 to 12 years. The only alternative was to get a third party supplier to manufacture the screens which entailed development and testing costs and the manufacture of an interface control board. This was done at an exorbitant cost. This demonstrates a typical real life problem.

Initial conversations with the Engineer [usually a Project Director (E&M) in the LTA context] and learned experts in industry showed that many were aware of the topic but oblivious to the potential problems that could arise. Therefore if any action is to be taken to combat end of life cycle challenges it had to be done sooner rather than later. To draw a parallel, in the planning of your retirement savings, it is important to plan now rather than to wait for retirement.

1.5 Research Objectives

The objectives of this research are:

- To provide an understanding of the complexity of transit systems, their technology and interfaces;
- To tap industry knowledge of what has been done with past systems that have been retired, rehabilitated or replaced;
- To formulate strategies from the standpoint of already operational systems at mid-life or near end of life; and
- To provide effective strategies for the future.

1.6 Research Approach

In meeting the objectives stated above, this thesis will firstly provide a breakdown of the civil and non-civil systems incorporated in the Singapore North East Line (NEL). The NEL system is a driverless metro utilizing state of the art technology in its daily operations. The technology used on NEL is typical of any rapid transit system in the world and given the author's familiarity with the system it is given as an example. An understanding of the complexity of the RTS system in terms of technology and interfacing serves to highlight the magnitude of the challenges that may be faced as the system nears end of life.

This follows a formal definition of the problem of system life cycle within the RTS context. The various life spans are given for the civil and non-civil systems and factors considered that determine and influence these life spans. Interviews were conducted with industry experts to gauge the awareness of the challenges at end of life and to identify any work that is being currently done in industry to address these challenges.

Based on the information gathered and experience, system strategies addressing social, economic and technical aspects of RTS end of life challenges are formulated. The advantages of each strategy are analyzed and appraised.

Future work recommendations on the execution of effective strategies are then given in the conclusion.

1.7 Thesis Organization

Chapter 2 provides a breakdown of the major civil and non-civil systems in NEL and accentuates the complexity of a typical transit system, the life spans of the various subsystems and the interrelation or interfacing of the various subsystems. A description of the development process of NEL is given and the associated system integration and testing the system underwent for commissioning.

Chapter 3 provides a systematic definition of the challenge and defines the performance over time of the subsystems of a RTS system, maintenance strategies and their influence on performance, the role of disruptive technologies in the RTS system, and finally interviews with industry experts. The chapter concludes with key findings from the literature review and interviews.

Chapter 4 develops and appraises system strategies that could address the challenges of end of life cycle. Two case studies are presented, one in Singapore and the other in London, to provide an understanding of what transit authorities worldwide are doing to address these issues. The chapter concludes with a discussion of four strategies: Public Private Partnerships (PPP), Reuse/Remanufacture/Recycle, Life Extension and Leasing.

Chapter 5 presents the conclusion and recommendations for future action.

Chapter 2: The Development of a Rapid Transit System

This chapter provides an understanding of the development of a rapid transit system highlighting its complexity, functionality of major civil and non-civil subsystems, and testing. With end of life cycle renewals or replacement it is envisaged that a similar barrage of design activities and testing would be required as with the development of a rapid transit system. Section 2.1 lists the objectives of this chapter.

To understand the development and complexities of a rapid transit system with its civil and non-civil functionality, an example is given of the North East Line (NEL) in Singapore (section 2.2). Although the RTS system consists of various subsystems, this chapter highlights those subsystems that can impact operations and are safety critical. A breakdown is given of the civil and non-civil subsystems (sections 2.3 and 2.4). The culmination of all these subsystems requires extensive testing for compatibility, safety and integration (section 2.5). Another aspect of the culmination of these systems requires the management of the interfaces and this in any development is the most formidable task (section 2.6). The chapter ends with a list of the approximate life spans which will be the focus of discussion in the next chapter (section 2.7)

2.1 Introduction

To appreciate the end of life cycle challenges of RTS systems requires an understanding of the functionalities, complexity and scale of RTS systems. This chapter describes the various civil and non-civil RTS systems and the scale of the integration testing required in particular for the non-civil structures. The life spans of the various RTS subsystems are given and the major interfaces within the civil and non-civil systems are identified. At end of life cycle of an RTS system it is envisaged that:

- With the replacement or renewal of RTS subsystems, a similar amount of testing would be required to ensure compatibility and system integration;
- The replacement or renewal of the RTS subsystems would need to take into account all civil and non-civil subsystems interfaces that are affected; and

- As a result of the scale of the replacement or renewals, detailed records of the maintenance and any lessons that are learnt throughout the life cycle of the rapid transit system should be kept. This would ensure that when an end of life cycle exercise is carried out, all parameters that may affect the exercise are accounted for.

The North East Line was commissioned on 20 June 2003 and will reach its mid cycle refurbishment in 2018 which is in 12 years and full cycle refurbishment in 2033.

2.2 The North East Line System (NEL)

Singapore is a tiny island state of about 692.7km, slightly more than 3.5 times the size of Washington DC with a highly mobile population[14]. The number of daily commuting trips has grown from 2.6 million in 1981 to 7.5 million in 1999 and is projected to increase to 10 million by 2010.

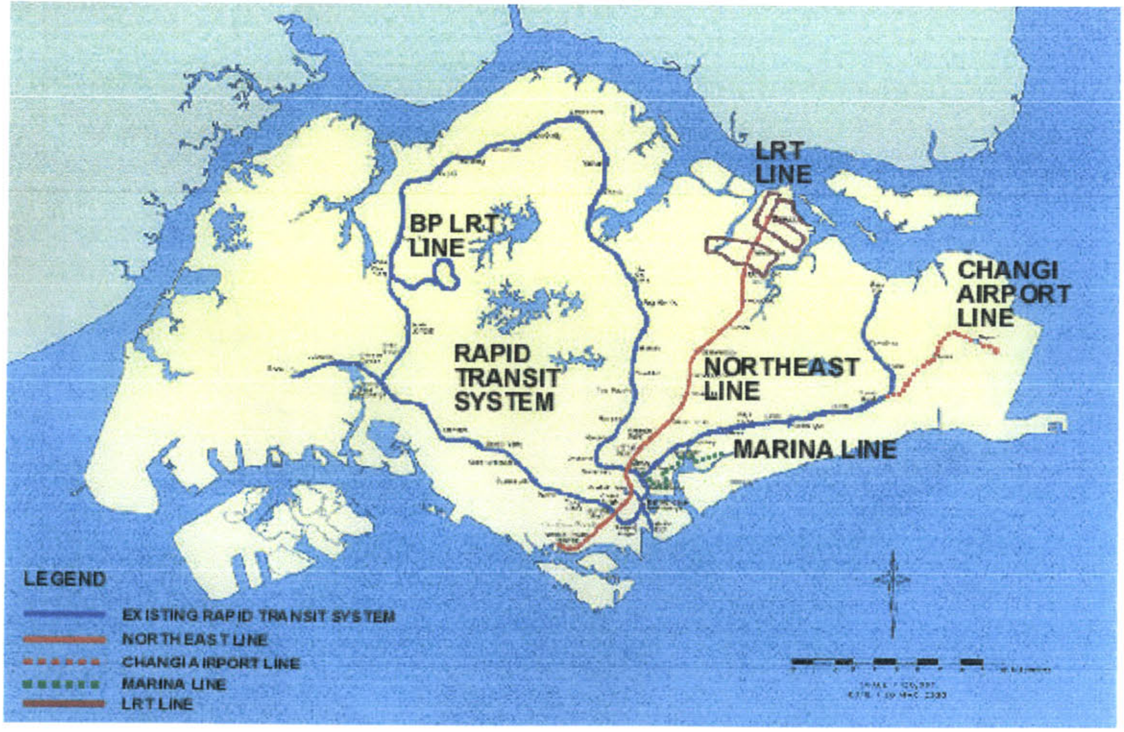


Figure 2-1: NEL and other transit lines in Singapore

In order to fulfill the Government's vision of making the rail network the backbone of the public transport system, the Land Transport Authority (LTA) of Singapore announced

---

[14] https://www.cia.gov/cia/publications/factbook/geos/sn.html

plans on 3rd January 1996 to invest S$20bn (approximately US$12.8bn) on high quality public transport over the next 15 years[15]. As a result, the government authorized the construction of a new line, the North East Line (NEL). NEL was one of Singapore's major rail projects to link the World Trade Centre in the south of the city with Punggol in the north. The entire project costs approximately S$5bn (approximately US$3.2bn) to build a rapid transit system, primarily underground, with full right of way protection. The Line was completed and launched into service on 20 June 2003 and currently carries about 250,000 passengers per day[16].

A detailed rail map of the Singapore rail system with NEL is given in Appendix 1. The rail map shows the lines that were built by period, for example the NEL (2003), North-South (1987) and East-West (1991-1996) lines. When these lines were built a lot of planning was done to ensure that these lines integrated seamlessly at their interchange stations. The point here is that these lines interface with each other in terms of technology, passenger flows and transfer amongst many other factors. While the focus of this thesis is on the end of life cycle challenges of subsystems in respective lines, the fact that these lines as a total system expire at different periods could also pose challenges at the end of life cycle. This argument is illustrated in Figure 2-2. In this thesis and as highlighted in the objectives set-out in Chapter 1, the focus will be on end of life challenges within the subsystems of lines.

---

[15] Anon., "White Paper launches metro bonanza", Railway Gazette International, Vol. 152, issue 2, p61, Feb. 1996.

[16] http://www.sbstransit.com.sg./generalinfo/operational.aspx#rail

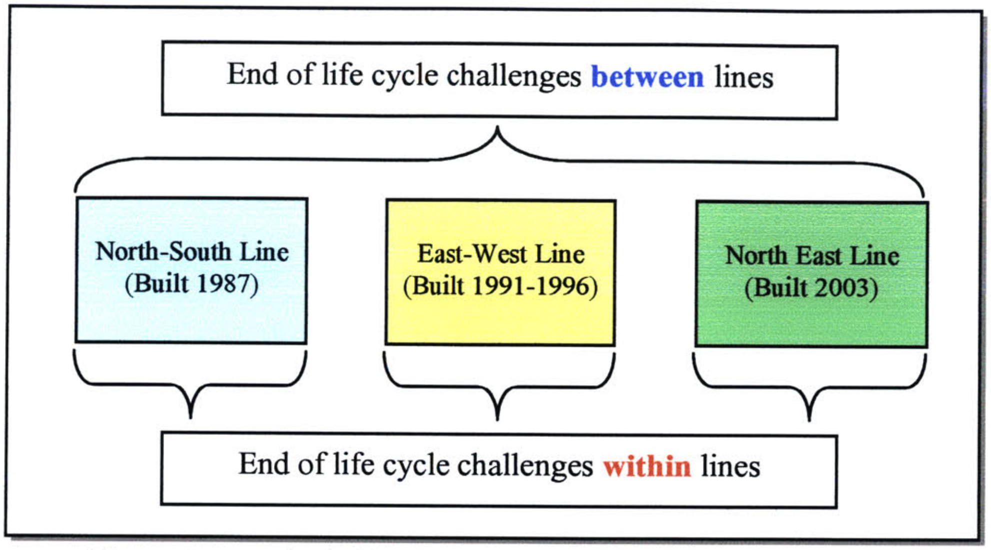


Figure 2-2: End of Life Challenges Within and Between Lines

2.3 Civil Systems Functionality

2.3.1 Tunnel Lining

Tunnel linings are used to provide the strength to the structure and at the same time prevent water ingress into the tunnels. This is evident for bored and cut and cover tunnels. The measured groundwater of rivers and canals, which pass over the NEL, contain relatively high levels of salinity. Experience from the existing mass rapid transit (MRT) lines had shown that a combination of low permeability concrete with a coal tar epoxy coating on the outer face could prevent the passage of groundwater through the body of the segment[17]. However, corrosion damage to the existing MRT line linings was apparent as this epoxy coating deteriorated over time. Thus for NEL, pre-cast concrete tunnel linings of 5.8m internal diameters are used throughout, with generally five segments plus key to form a ring of width 1.2m. Hydrophilic materials are used to seal the segment joints and concrete durability is enhanced by the use of silica fume and coal tar epoxy coating on the segments[18]. Even with these hydrophilic materials, water ingress still seems to be a problem and water ponding and corrosion are still seen along the NEL line as well as older lines lines. In 2003, water dripping on the third rail power ceramic ring shorted out a section of the north-south line in Singapore

---

[17] R.Krishnan, J.P.Copsey, R.G. Algeo & J.N. Shirlaw, "Design of the civil works for Singapore's North East Line", Tunnelling and Underground Space Technology, Vol. 14, No.4, p433-448, 1999, Elsevier Science Ltd

[18] T.W. Hulme & A.J. Burchell, "Tunneling project in Singapore: an overview", Tunneling and Underground Space Technology, Vol. 14, No.4, p409-418, 1999, Elsevier Science Ltd.

rendering the line inoperable for half a day and requiring passenger evacuation from the tunnels. In this respect, the issue of water ingress should not be glossed over and can cause considerable impact on operations and safety.

The durability and life span of these hydrophilic materials are questionable and for the earlier lines, the use of the coal tar epoxy will be an issue over time. Given the tunnels are rated for a 120 year life span; water ingress will impact the non-civil infrastructure for example power supply, signaling and communications equipment. Therefore in the decision making process of renewals or replacement these factors should be considered.

2.3.2 NEL Stations

All stations in NEL are underground with a platform of approximately 140m long. Most of the NEL stations have two levels: a concourse level and a platform level, although, two stations (Outram Park and Dhoby Ghaut) have up to five underground levels because of the depth needed to allow the NEL tunnel to pass under the older MRT tunnels. This is one example of different lines interfacing with one another.

Some of the NEL stations provide Civil Defense (CD) shelters. These station shelters are designed to operate as transit stations during peacetime and as CD shelters during emergency (i.e., to withstand weapon effects such as blast, shock, unhealthy air caused by the explosive combustion.)[19]. Given that these facilities are part of the stations but more under the purview of the Singapore Civil Defense Force they are not considered in the development of end of life strategies.

2.3.3 Track Work

For NEL, slab track was used providing the advantages of eliminating the risk of track buckling and reduced required maintenance. However, the drawbacks include high initial cost

---

[19] W.K. Bernard Tan, J.C. Chin, C.K. Lee & K.F. Wong, "Planning and design of a Civil Defense Shelter in Singapore", Tunneling and Underground Space Technology, Vol. 14, No.4, p509-512, 1999, Elsevier Science Ltd.

and high noise levels compared to ballasted track. Vibration transmission through the concrete slabs to adjacent structures and its surrounding can be substantial[20].

To ensure precise positioning of the track fastenings, accurate setting of the track gauge and speeding up the track laying process, reinforced concrete sleepers, embedded in the in-situ concrete were selected. These components do not have significant impact on the end of life cycle as long as they are properly maintained.

Rail has a design life of 30 years. The rail selection is based on factors which include axle load, rail support geometry and maintenance requirements. UIC60 (i.e. 60kg/m) rails are used to provide track gauge of 1435mm for NEL. Different rail grades are used on different sections of track. For example, the UICGrade900A (with hardness not less than 260HB[21]) is used on tangential track or curved track below 800m with rails on tighter radii being head hardened (with hardness between 340 and 390HB). The manner in which the rails are connected also varies and rails are welded using the electric flash-butt welding process, except at turnouts, where thermit welding is allowed. The key determinant of the end of life decision for rails lies with the wheel-rail interface. With the renewal and replacement of rolling stock for example, assessments need to be made on new loadings imposed on the rails, lubrication requirements at curves and ping-ping frequencies at the electric and thermit welds.

Being a fully automatic railway, with no operational need to have train crew on board, turnouts are monitored using remote sensors at all switches where unheralded failure will risk disrupting services. By monitoring the current drawn by the point motors and the force required to throw the switches, adverse conditions can be corrected before they result in an actual failure. The efficiency of the sensors and motors need to be evaluated throughout the life span of this system and taken into account at end of life.

---

[20] J.E. Whitbread, "Slab track and non ballasted track", Paper 3.14, Third Track Sector Course (Railway Civil Engineering), Railway Industry Association, London, Lontec Ltd, 1989.

[21] HB = Brinnell Number, a measure of metal hardness.

2.4 Non-civil Systems Functionality

2.4.1 Tunnel Ventilation System

It is apparent that one of the most critical considerations for mass transit tunnel design is sound environmental control. This system includes temperature and humidity control, circulation of fresh air and safety features in the event of tunnel fire. As with other systems, substantial project savings are achieved with reduced number of vent shafts without compromising the effective functionality of the entire ventilation system under both normal and emergency situations[22]. Although these systems do not encompass advanced technology in their architecture, the efficiency of these ventilation/extraction systems is vital to the safety of commuters in the tunnels. With time, the motors and bearings may age causing the efficiency of these systems to dwindle. Such reductions in efficiency impact the number of trains that can run in the tunnel segments and also have an impact on the trains own emergency ventilation systems. Therefore such factors should be taken into account at end of life of these systems.

2.4.2 Power Supply System

The supply voltage for NEL is 1500V DC. Under normal operating conditions, the electrification system will be fed from traction substations, locating at seven points along the main line, with intermediate power paralleling points known as tie-breaker substations. A traction substation exists at the NEL depot (NED) and will be dedicated for the depot Overhead Current Supply (OCS) system only. A total of four inverters (including the one in depot) will be provided at traction substations, to invert regenerative braking energy of the trains back into the 22kV system[23]. The efficiency of the inverters varies over time and the uses of regenerative braking imply an interface with the rolling stock. Therefore any changes to the rolling stock or inverter substations would impact both systems and vice-versa.

The feed from the traction substations also powers up the NEL stations and other stations on other lines which are in close proximity with the NEL line. Given the power

---

[22] Urban Mass Transport Administration, "Ventilation and Environmental Control in Subway", p16-17, TR News, November-December 1987, United States.

[23] Land Transport Authority, "Design Criteria Specifications for Contract 759", Singapore, approx. 1997.

systems are intermeshed the renewal or replacement of the power supply system would need to consider this.

2.4.3 Overhead Collection System (OCS)

The OCS equipment is designed for a life span of 50 years to cope with the annual distance run per train of approximately 120,000km, with daily operation of up to 20 hours. The design philosophy for all aspects of the OCS is based on proven technology to achieve efficient, reliable, safe and cost-effective operation.

2.4.4 Stray Current Corrosion Control

A continuous conductor, running along the tunnel wall is the key component in an improved system for detecting and controlling stray currents. Collection mats in the track bed concrete well are installed in discrete lengths of 10m. The purpose of stray current corrosion is the prevention of electrolytic corrosion. A degraded or inefficient stray current corrosion control system could cause irreparable damage to civil infrastructure and hence its effectiveness and efficiency should be considered at the end of its life cycle.

2.4.5 Rolling Stock

The NEL trains are comprised of two Driving Trailer (DT) cars, two Pantograph Motor (Mp) cars and two Intermediate Motor (Mi) cars. The trains are138.5m long and 3.2m wide and can accommodate 1620 standing and 296 seated passengers.

To enhance the reliability of the train without a driver, all major systems have built in redundancy. This is an important factor to consider in the future refurbishment of trains. The higher degree of redundancy ensures that a single point failure or system failure does not immobilize a train. Critical components have been doubled in quantity and controlled by different train circuits, and similar groups of equipment installed at different locations of a train are interlinked by a Master and Slave configuration to allow for faulty components and degraded modes of operation.

The trains feature enhanced safety and security features. In the context of safety for example the trains are equipped with heat (fire-wire) and smoke detectors that will alert OCC immediately should there be a problem. Each car includes 10 smoke detectors and numerous heat sensitive wire loops passing through the underseat and underframe equipment compartments.

Security features entail the use of two closed circuit television (CCTV) cameras in each car that monitor passenger activity. The feed from these cameras are stored on onboard recording devices and at any time OCC can plug into the feed to ascertain problems in a particular train.

Thus, the trains consist of a wide array of subsystems with their own separate life spans. The expiration of these subsystems would impact both the internal subsystems and the external subsystems in the RTS system with which they interface.

2.4.6 Depot Equipment and Maintenance Vehicles

The depot for NEL covers an area of 27 hectares[24] in area to the north of Singapore. It consists of the following:

- Stabling positions for 20 six car trains with space for an additional 24 trains should the need arise in the future. This area, plus a buffer siding area for 3 further trains, is also equipped for interior cleaning of trains. The design of the depot is completely under cover with the deck above being available for future commercial or light industrial development[25].
- An examination building which includes light maintenance facilities such as an Underfloor Wheel Lathe for regular re-profiling of wheels.
- A main workshop that features heavy maintenance and equipment overhaul facilities such as bogie washing plants, wheel extraction facilities, heavy lifting equipment etc.

---

[24] This plot size sounds considerable for a depot to maintain 25 trains and a 20km line. However, the plot incorporates a buffer for future fleet size expansion to cope with increased traffic demands.

[25] This feature of making available the top of deck for industrial development exists for two depots in Singapore. The first being the Ten Mile Junction Depot serving the Bukit Panjang Light Rail Transit (*Bombardier CX-100*) system and the second being for NEL.

- A train washing plant for regular exterior washing and underframe washing of trains.
- A locomotive workshop for maintenance of Battery Locomotives, Wagons and special vehicles.
- A test track for train testing in automatic mode at speeds up to 70km/h.
- A central warehouse for storing spare parts required for effective maintenance of the whole railway.
- A main office block that houses the NEL Operator, OCC and Depot Control Centre (DCC).

It is typical for depots to be sized to allow for future expansions. The impacts of end of life challenges on depots or expansions are minimal. The reason being that the equipment in depots are standalone equipment and renewal or replacement of these equipment would not cause serious impact on operations or technology.

The maintenance vehicles consist of battery locomotives, flat wagons, high-level access wagons with cherry picker, heavy duty crane, tunnel cleaning wagon, rail grinding vehicle and multi-function vehicle. Again these rolling stock are designed to work as individual entities and their interfacing with existing subsystems on the RTS system are minimal.

2.4.7 Signaling

The NEL signaling system is a moving block system. On a moving block equipped railway, the line is usually divided into areas or regions, each area under the control of a computer and each with its own radio transmission system[26].

The NEL network is divided into seven signaling areas of control for the mainline and two signaling areas of control for the depot. Each area of control is known as an ATC (Automatic Train Control) sector and has a computer located in the main station which is in turn connected to several WIN base stations by serial links (Figure 2-3). This system is employed on the NEL trains using WIN (Waveguide Information Network). The WIN is a bi-

---

[26] http://www.railway-technical.com/sigtxt3.html

directional continuous transmission system between the track and the train and is a displacement measurement system.

Information or communication throughout the network is through a radio-based transmission system. The revenue line is usually divided into sectors or regions, each sector being under the control of a computer and each with its radio transmission system. Status reported includes the trains' identity, location, direction and speed, information on which is shared collectively amongst all the trains running on the tracks. When a train reaches the boundary of a new sector, the computer of the first sector contacts the computer of the second sector and alerts it to listen for the new train's signal. The handover between sectors in shown in Figure 2-4.

In signaling systems much of the upgrade of the system is a replacement exercise. Traditional signaling systems were fixed block and with the advancement of technology over the past decade, moving block signaling has become the minimum requirement for new RTS systems. Thus, it is envisaged that fixed block systems will be replaced by moving block in the future.

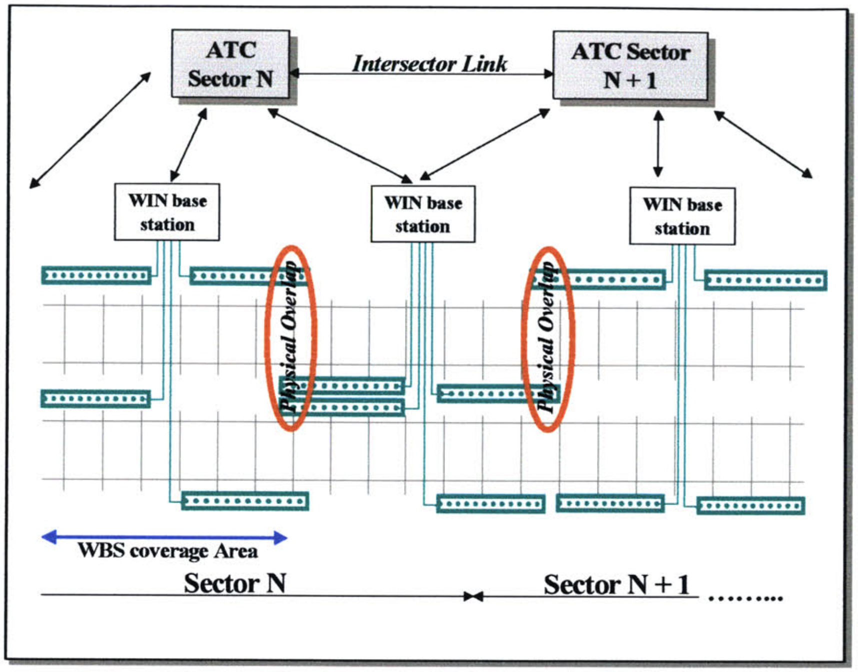


Figure 2-3: ATC network description

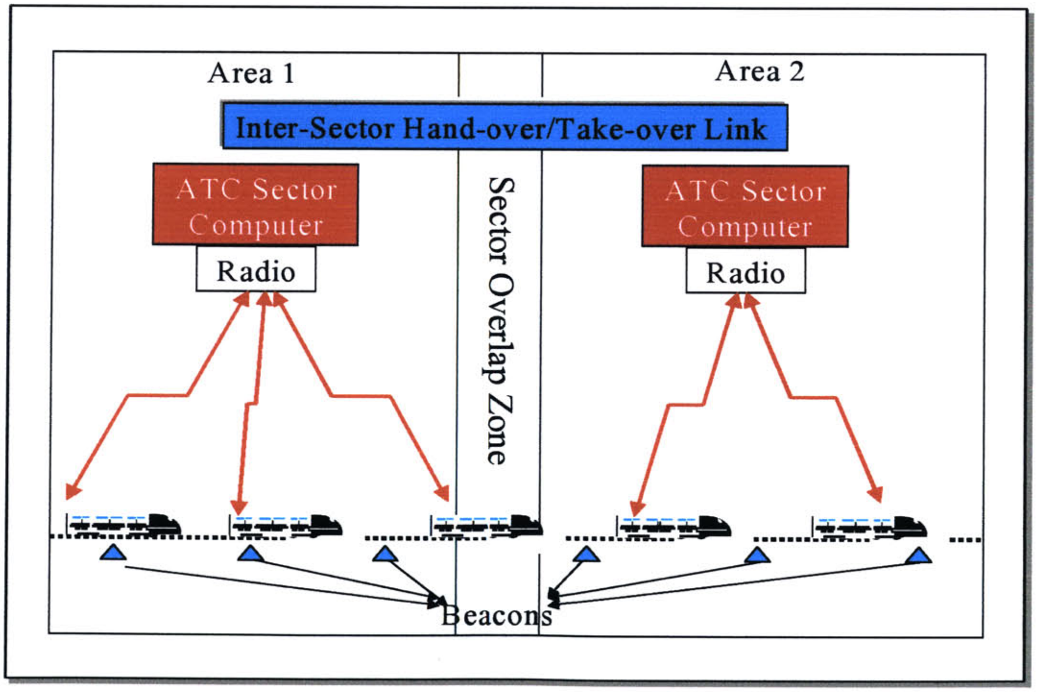


Figure 2-4: Inter-Sector Hand-over/Take-over Link

2.4.8 Platform Screen Doors (PSDs)

Platform Screen Doors (PSDs) are installed at all NEL underground stations. These doors are designed to provide a high level of passenger comfort (reduce the amount of inhalation of dust and airborne particulate in the tunnel, which may pose a threat to the human respiratory system) and to ensure their safety (prevent people or objects from falling onto the tracks and avoid the costs arising from such disturbances). Experience with the existing rapid transit operator has revealed that substantial energy savings (approx. 50 % energy cost savings) can be achieved for the station air conditioning through the installation of PSDs.

The wear and tear on PSDs are substantial given these doors open and close well over a millions of cycles. While the actual doors do not require replacement, the working parts including motors, gears and actuators would need to be replaced. The impact on operations is minimal if the work is planned and action appropriately.

2.4.9 The Integrated Supervisory Control System (ISCS)

The ISCS is the 'brain' of the NEL system. To provide overall supervision, an Integrated Supervisory Control System (ISCS) is installed at the Operation Control Centre (OCC) system which brings various railway systems such as rolling stock, signaling, power, fire protection, maintenance management[27] system together as an integral system. [28]

The primary components of the ISCS consist of:

- An integrated Control Management System (CMS) at the OCC to provide the operator with the facilities to monitor and control various systems and equipment in the railway;
- Depot Control System (DCS);
- Station Management System (SMS) at each station; and
- A Plant Management System (PMS) at each station to provide interface with the various systems and equipment to be supervised.

---

[27] Maintenance Management System (MMS) is used to monitor the health of each asset, status of equipment, fault history, cost & replacement value. This system helps to enhance the level of availability of major systems in the NEL.

[28] See Tow Pak Wei, Leong Kwok Weng & Chew Tai Chong, "The Singapore Rail Network For 21st Century A Driverless Mass Transit Network", Singapore, approx.1999.

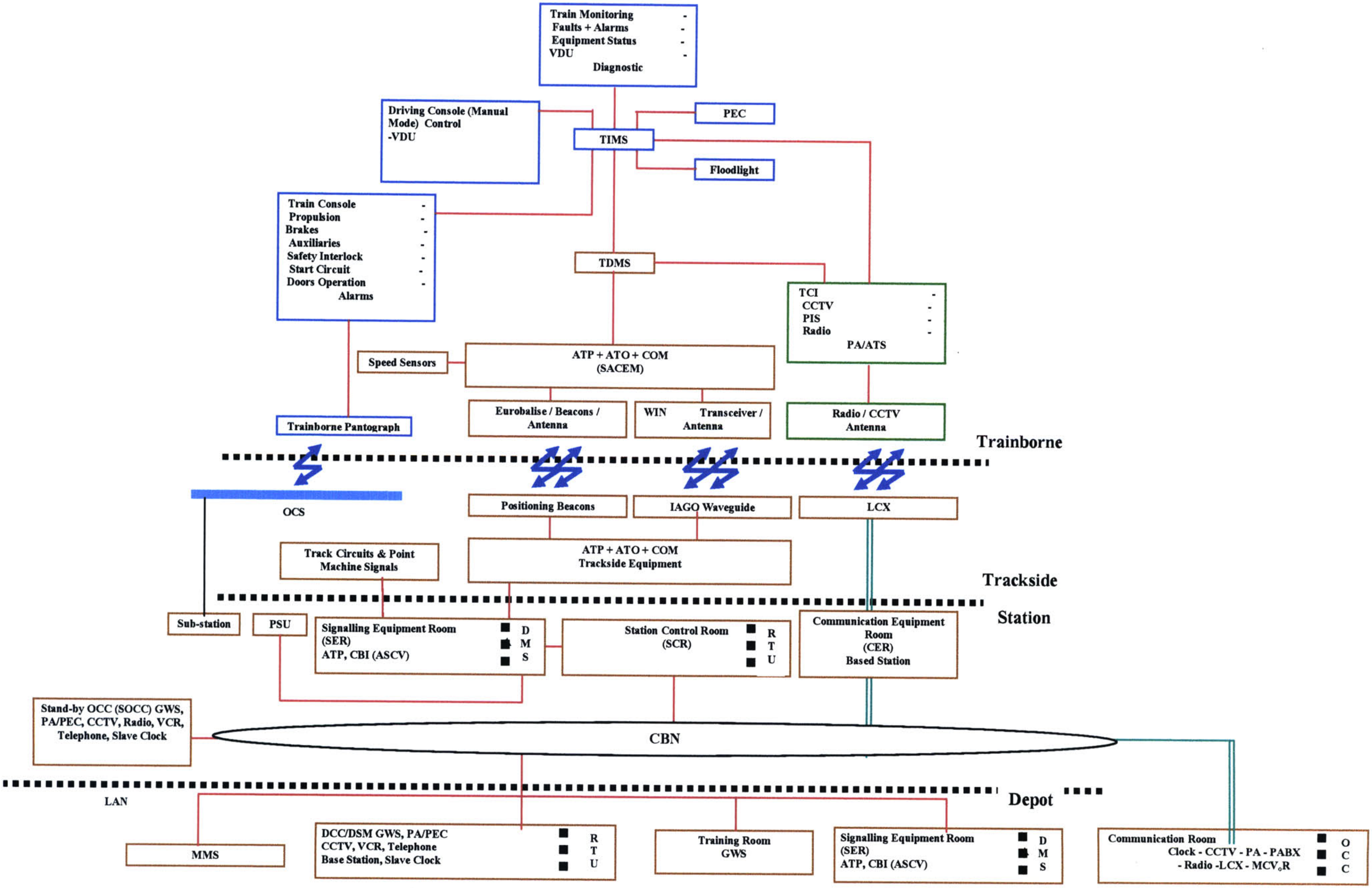


Figure 2-5: Overview of the ISCS System Architecture

The ISCS system is primarily software driven and to achieve scale as shown in Figure 2-5 the various systems are interlinked to provide the functionality required to run the RTS system. The software inevitably goes through many revisions and in fact for NEL, the latest revision as of December 2005 was version 14.7. The end of life of a software system occurs typically when:

- The language in which the software has been written becomes outdated;
- The software has been heavily patched and is beyond further modification; and
- The system is unable to meet the demands in terms of capacity and speed required to service the RTS at the required level.

2.4.10 Communications

The NEL communication system consists of a Radio Communication System (RCS) which has a main and standby switching control node located at the OCC and 17 base stations. As NEL is an underground system, a leaky coaxial (LCX) cable distribution network is used to ensure that the voice and data signals are propagated to all the intended areas of the system.

The safety of the passengers traveling in the NEL system (the fully automated operation without driver on board the train) is of paramount concern. Therefore, there is a need for passengers in the trains to communicate with the Operators at the OCC in any unforeseen emergency. The communication link can be established via the Emergency Call Buttons (ECB) which are provided on-board trains. A loudspeaker is situated adjacent to the ECB allowing OCC to reply directly to the passengers. Additionally, Public Address (PA) systems are installed in all stations and trains to allow the Operators from OCC and station control room to make live or recorded announcements to all passengers. As highlighted under the rolling stock description, closed circuit television (CCTV) cameras are also provided in the stations and on board the trains for surveillance purposes. This feature is particularly important given the current worldwide security climate.

2.5 System Testing and Integration

The development of an RTS system requires an immense amount of testing to ensure that all systems are integrated, safe and compatible. It is envisaged that with the replacement or renewals of RTS subsystems, a similar amount of testing would be required to ensure compatibility and system integrity. On NEL, the system was developed on a piecemeal basis first, with individual systems developed separately and then being brought together for functional testing and eventually full scale testing. Figure 2-6 shows the development and testing process.

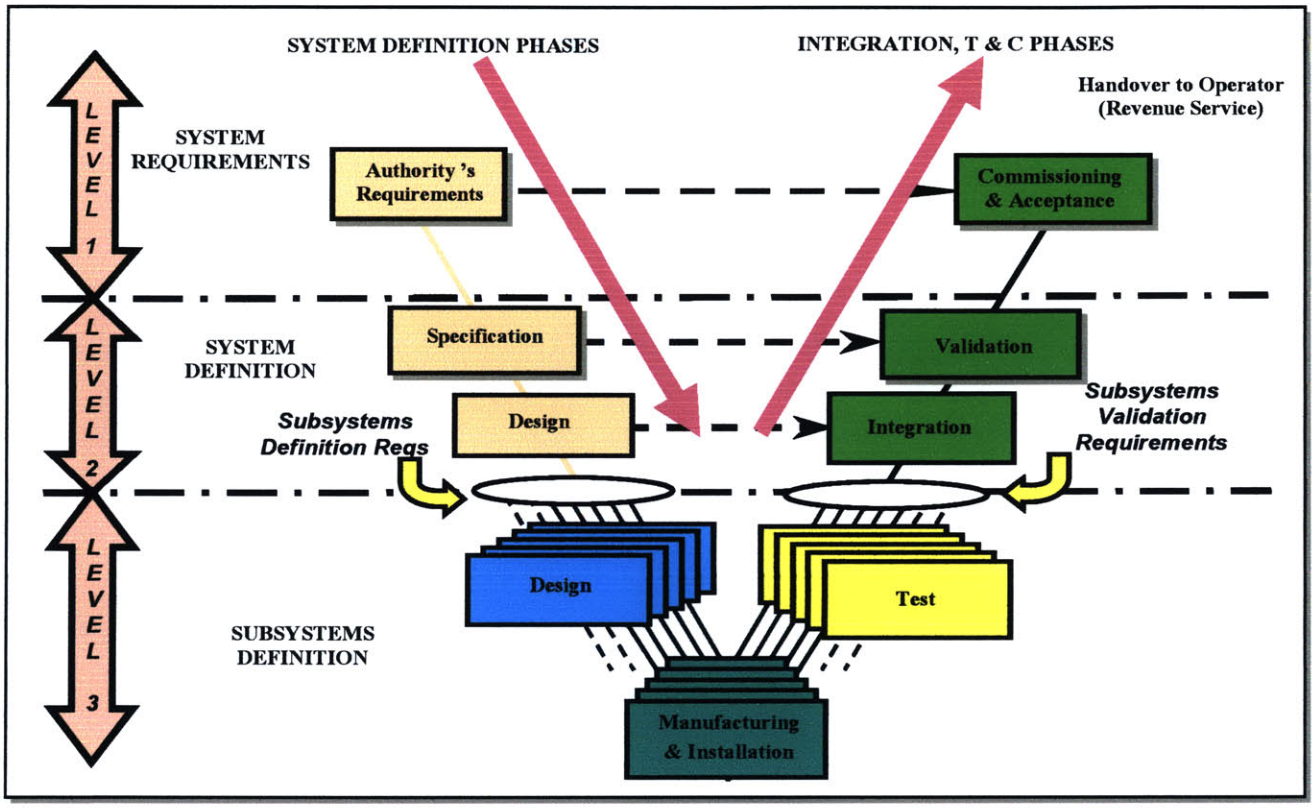


Figure 2-6: V-Development Process for RTS Systems

With the renewal or replacement of subsystems, the above process would need to be adhered to. The critical path of the above verification and validation diagram is the right side dealing with testing and integration. The aim of this leg is:

- To verify and validate the integration and validation of the subsystems;
- The demonstration of system operability and functionality; and
- The demonstration of system performance.

For NEL Table 2-1 lists the total number of tests needed which accentuates the point that at end of life cycle, a similar number of tests would need to be conducted with the added challenge of ensuring minimal impact on the operational RTS system.

Description	*Number of Tests*
Stand Alone System Testing (STC)	3915
Integrated Testing and Commissioning (ITC)	774
Test Running Activities	82
Total Number of Tests	**4771**

Table 2-1: Total Number of Tests Conducted in the Development of NEL

2.6 The Management of Interfaces

The replacement or renewals of the RTS subsystems would need to take into account all civil and non-civil subsystems interfaces that are affected. The previous sections have described the major subsystems within the civil and non-civil subsystems and Figure 2-7 shows that while the subsystems themselves are complex and complicated, the labyrinth of other subsystems that they interface with also demands attention. To renew or replace these subsystems affects other systems as well and requires an equal amount of attention.

On the North East Line the management of the interfaces was left to a private contractor. This contractor eventually abandoned the contract as it felt that the management of the various contractors and their respective civil and non-civil systems was an impossible task. The Singapore Land Transport Authority (LTA) has learned from this and now for the new Circle Line a turnkey contract was awarded and the responsibility for integration left to the Contractor. This point accentuates the complexity and difficulty associated with the management of interfaces.

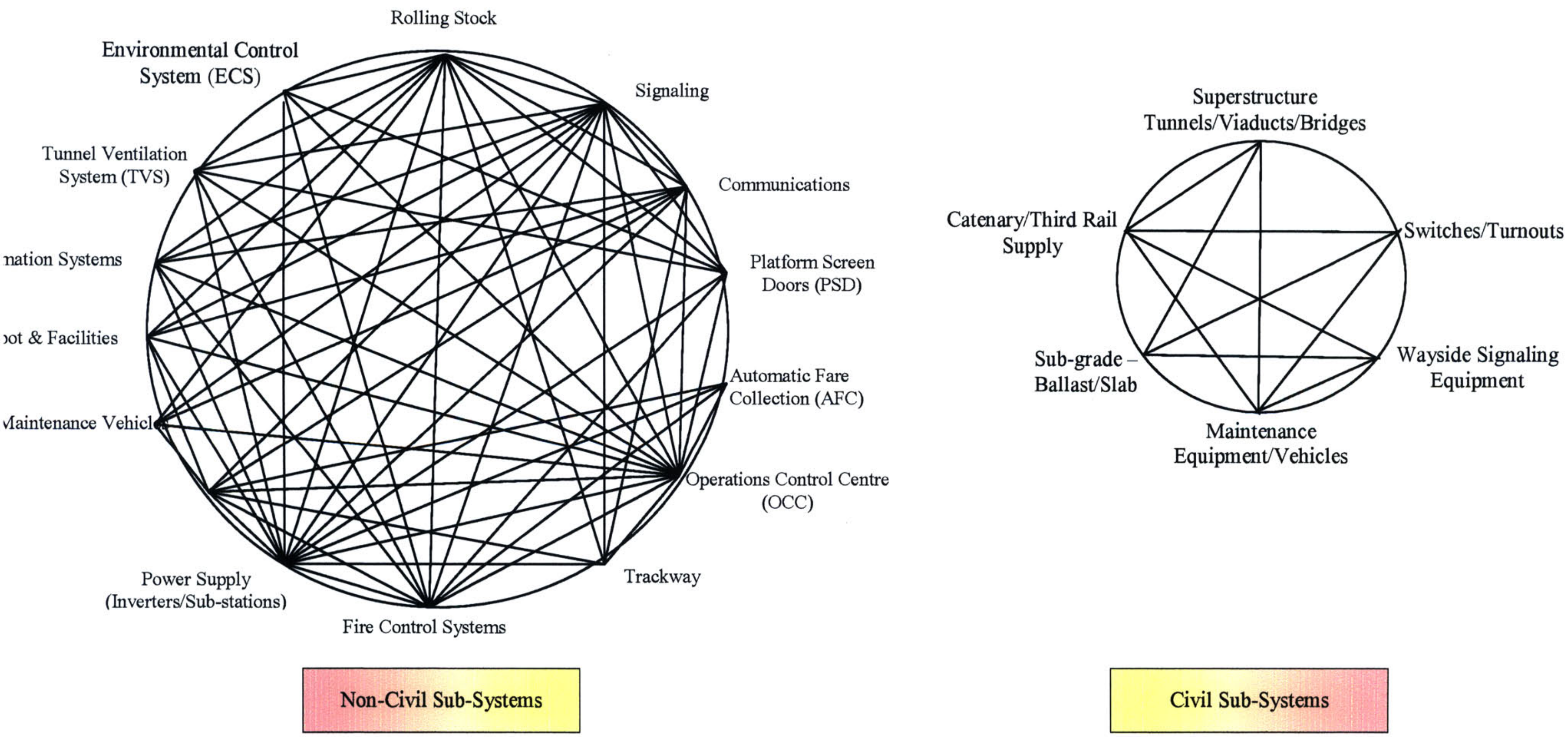


Figure 2-7: Inter-relation of the Civil and Non-Civil Interfaces

2.7 Lifespan of Civil, Electrical and Mechanical Infrastructure

Tables 2-2 and 2-3 below summarize the various infrastructure described in the preceding sections with their expected lifespan. The figures highlight the argument in Chapter 1 of different RTS civil and non-civil subsystems expiring at different times. These life spans will be discussed further in the next chapter.

Civil

Description	Estimated Life Span (years)	Remarks
Tunnel Lining	120	
Platform Screen Doors	30	
Slab Track	120	
Rail	5-6	
Turnout Monitoring System	15-20	

Table 2-2: Typical Life Spans of Civil RTS Sub-systems

Electrical and Mechanical

Description	Estimated Life Span (years)	Remarks
Train (Rolling Stock)	20	Propulsion Equipment
	15	Auxiliary Equipment
	30	Interior Fittings
	15	Electronic Equipment
Permanent Way Vehicles (Track Maintenance Equipment)	25	Chassis and Structure
	15	Engines & Transmission
	15	Electronics and Software
	25	Auxiliary Equipment
Power Supply (Equipment and Cabling)	25	Switchboard Transformers and cables
	25	Electrical Relays
	20	Rectifiers/Inverters
	20	UPS and Battery Banks
Supervisory Control System	15	SCADA System
Escalator & Lifts	15	Chains, motors and drives
	15	Steps and Control Systems

	30	Lift Car and Truss
Platform Screen Doors	20	Door Operating Gear
	20	Air Receivers/Compressor
Environmental Control System	15	Heat Exchange System (stations, OCC)
	30	Mechanical Ventilation System
	15	MCCs and sequential controllers
Electrical Service and Fire Protection	15	Fire Protection Systems
	20	LV Distribution and Lighting System
	25	CD Generators etc.
Signaling System	15	ATS
	15	ATP/ATO
	30	Interlocking
Communication System	15	Backbone Network
	15	Radio System
	7	CCTV
	15	Public Address
	20	Emergency Trip Stations
	15	EPAX/PABX
Automatic Fare Collection System	20	Gates
	7	Computers (Central, Station and ECU)
	12	Ticket Vending Machines
	12	Booking Office Machines
	12	Encoder/Sorter
	12	Note Changing Machine
Depot Workshop Equipment	25	Under floor Wheel Lathe
	25	Above floor Wheel Lathe
	15	Train Wash Plants
	15	Equipment Wash plant and Water Treatment Facilities
	25	Lifting Roads
	20	Paint Shop Equipment

Table 2-3: Typical Life Spans of Non-Civil RTS Sub-systems[29]

---

[29] Table from Land Transport Authority Replacement Grant – Authored by Leong Kwok Weng, Lim Hock Meng, Lin Min and Ajmer Singh Kairon

Chapter 3: Problem Definition

This chapter defines various terms and introduces the problem (section 3.1). It then describes the behavior of RTS systems as they age through performance versus time/age plots. The activities of preventive maintenance, rehabilitation and eventually replacement are explained (section 3.1.1). The interactions of the numerous RTS subsystems add to the complexity and scale of the renewal or replacement exercise and are described (section 3.1.2). Maintenance activities are bound to affect the end of life cycle of RTS systems and are further discussed (section 3.1.3). The role of disruptive technologies and their implications on RTS systems are broached (section 3.1.4). A summary of interviews conducted with a manufacturer and operator on their views of end of life cycle challenges with RTS systems is presented (section 3.2).

3.1 Problem Definition

Chapter 2 has described in detail the major subsystems that comprise an RTS system. In this section one objective is to define the terms used throughout this thesis, some of which were briefly introduced in Chapter 1. It also provides a definition of the problem of end of life cycle and other factors that may aggravate or hasten the expiry of the RTS subsystems. The following subsections will discuss the topics below and their influence on end of life challenges of RTS systems:

- Performance versus time of the RTS system: The fact that the RTS system is comprised of subsystems that do not have consistent life spans exacerbates the renewal or replacement of these subsystems. A piecemeal approach of continual renewal or replacement of individual subsystems is going to be costly, disruptive to operations and a technological challenge given the complexity of the RTS system;
- Interactions of the non-civil RTS subsystems: Figure 2-7 has shown the interfaces of the individual civil and non-civil RTS subsystems. The renewal or replacement of these individual subsystems will definitely impact the performance of the other RTS subsystems it interfaces with. This section provides an interface matrix of these interactions and explains the extent of the problem;
- Maintenance Strategies and their Influence on the Life Cycle of the RTS: The type of maintenance strategy adopted be it preventive maintenance, reliability centered

maintenance etc. also plays a part in the performance, wear and tear and ultimately life span of the RTS subsystem.

- Disruptive Technologies in the RTS: A disruptive technology leads to the early retirement of the incumbent technology. The role of disruptive technologies and their impact on the life span of the RTS subsystems is discussed in this section.

The term *RTS system* here is defined as a collection of different systems or elements, which, working together, produce a result not achievable by the systems alone[30]. Here the system refers to the technical system. From the implied definition of the system above, it is inferred that any system is part of a larger system while also having its own sub-systems. Figure 3-1 categorizes the major RTS sub-systems.

The term *legacy system* is defined as a system reaching its obsolescence/maturity or the end of its life cycle or useful life. Some refer to these systems as antiquated systems[31]. It is a system within an evolving environment contributing to the erosion of the system and making it no longer able to satisfy core business requirements[32]. Legacy systems can also result because of advances in technology that cause the early termination of the system for example with the introduction say of disruptive technologies. This will be covered in a later section in this chapter.

As an RTS system nears the end of its life cycle, it effectively becomes what is termed a legacy system. Research shows that there is no concrete definition of a legacy system. In fact, it was noted that the definition of a legacy system has changed over time and the literature has shown a progression from addressing only the technical perspective to encompassing the wider socio-technical issues of legacy systems[33].

---

[30] Maier, M.W. & Rechtin, E., The Art of Systems Architecting, CRC Press, 2002

[31] http://en.wikipedia.org/wiki/Legacy_systems

[32] Brooke, C. & Ramage, M., Organizational Scenarios and Legacy Systems, International Journal of Information Management, 2001

[33] Implications of the Theories of Complexity for the Co-evolution of the Business Process & Information Systems Development, EPRSC Review Report, Grant GR/MO2590/01

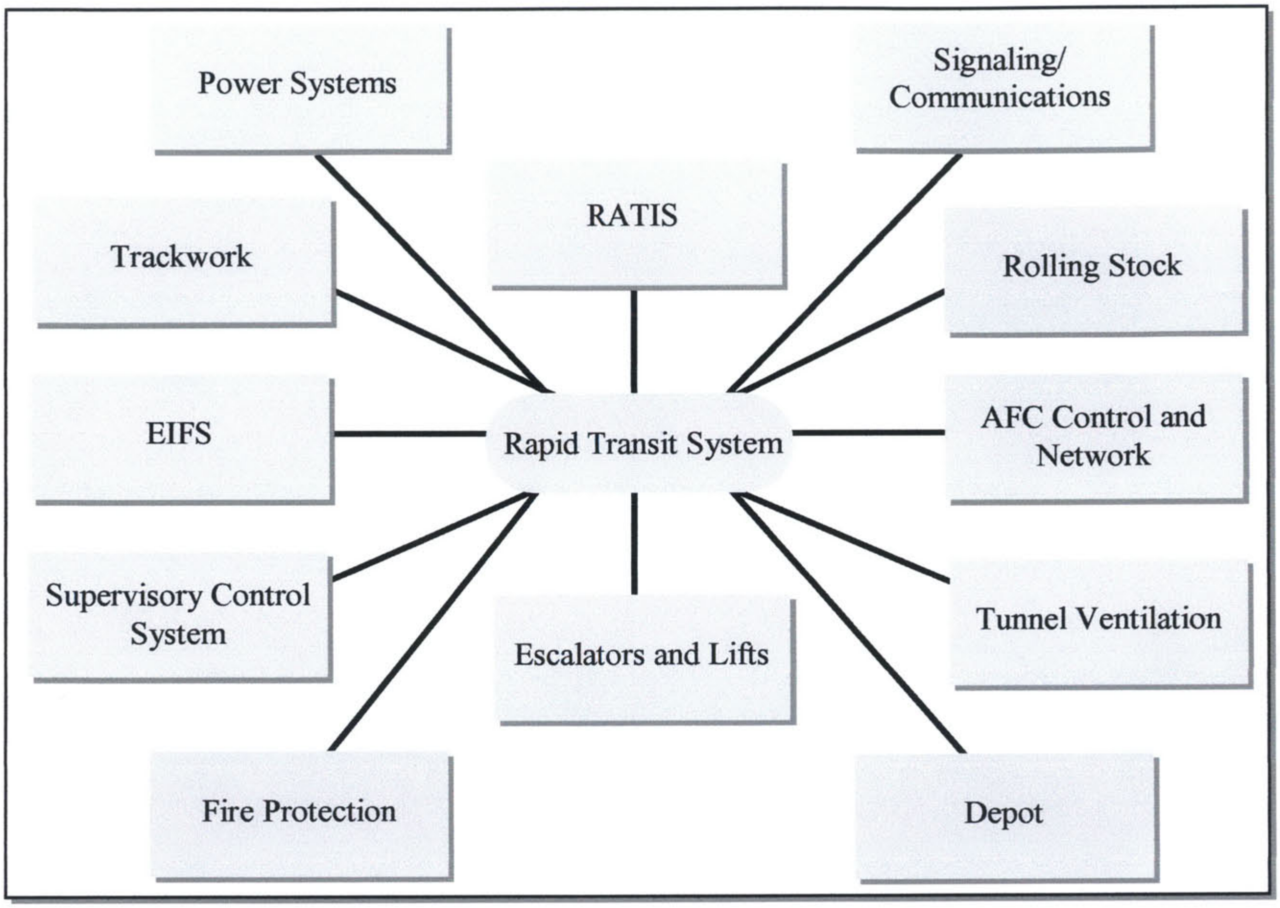


Figure 3-1: Examples of various subsystems of the RTS

The literature search showed that software is the focus with regard to legacy systems or end of life cycle challenges. This is logical given the dynamic nature of software upgrades and releases rendering code written years or even months back as outdated. In the software arena it is noted that "Legacy systems have been described as vital to the organization but we don't know how to cope with them"[34]. By drawing a parallel to products or hardware systems we can see that the phrase "don't know how to cope with but that are vital to our organization" is equally applicable.

In the RTS context, as a system matures, it moves along the road to obsolescence. The maintenance requirements would inevitably increase as the system ages and requires components to be replaced as a result of failure or typical wear and tear. Rapid technology advancement may also lead to component replacement. The owner or operator of the RTS system reacts to these changes in a piecemeal manner, changing out components as needed. It may come to a point

---

[34] Bennett, K., Legacy Systems: Coping with Success, IEEE Software, 0740-7459/1994.

where RTS subsystems need to be replaced and if this is the case how does the operator react. Is this reaction too late given the replacement of the RTS subsystem requires advanced planning and huge capital injection? Thus, it becomes a situation where the operator does not know how to cope. If this is the case, the RTS system performance deteriorates and enters a declining performance cycle.

However, a scenario of RTS subsystems/components becoming obsolete does not always mean a system is not performing optimally. It may be the case that the RTS subsystem is performing but is no longer compatible with other RTS subsystems it interfaces with. The other RTS subsystems might have been upgraded or enhanced. These challenges also add to the complexity of end of life cycle strategies. In the context of information systems, it is noted that integration with other systems may be hampered by legacy systems whose interfaces need upgrading or replacing[35]. In modern RTS systems one such example would be the Integrated Supervisory Control System (ISCS) or in older systems the SCADA (Supervisory Control and Data Acquisition) system. Given the mismatch of life spans between the ISCS and say for example Rolling Stock (see Table 2-3), once a change happens with either system, a substantial amount of testing and validation needs to be carried out to ensure that the systems remain synchronized and well integrated. This testing and validation is needed to reduce the risk involved in re-engineering legacy systems. In fact, it is noted in the literature that when replacing a legacy system, people often underestimate the amount of risk. Risk manifests itself as exceeding budgetary constraints of a failure to satisfy functional requirements[36].

There is the additional scenario of the extension or expansion of the rapid transit system which inevitably forces the upgrade of systems. The extension or expansion of the line could render existing sub-systems irrelevant based on inability to cope with the demands of say increased passenger ridership. In any extension or expansion one subsystem of the RTS that is more directly impacted is the Signaling system. Typically these changes come after decades of product use and one example highlights the extent of work required in terms of cost and complexity. A rapid transit railway in Switzerland was planning an extension of their system in

---

[35] Bisbal, J. et al, Legacy Information Systems: Issues and Directions, Trinity College Dublin, 1999

[36] Stephen Adolph, W., Cash Cow in the Tar Pit: Reengineering a Legacy System, IEEE, 1996

1989. The Signaling they employed was a 1971 legacy system and the Operator was facing a number of problems including[37]:

- The host computer of the signaling system was a General Automation GA900 which was becoming difficult to obtain and service. In addition, the system was being deployed to handle increasingly larger transit systems, and the number of trains the system could manage was limited by its processing capacity;
- Memory limitations imposed by the host computer limited the information that could be stored about a train and the guideway; and
- Maintaining code was difficult because there were few programmers who had ever heard of – let alone programmed in GA900 assembly language. Moreover, after years of evolutionary development and bug patches, much redundant code had accumulated in the system. If further changes were to be made, it entailed laborious searches to find the relevant code to be modified.

As a result the operator requested a replacement of the old system. Apart from the cost of the replacement the challenge remained that this needed to be done while still maintaining the current railway in operation i.e. this exacerbated the complexity of the replacement. The teams managed to replace the existing signaling system by separating the functions of the current system for example, train monitoring, polling, track switches, automatic train operation and replacing each of these functions with the new system. Figure 3-2 shows the 12 development stages for the replacement divided according to function.

---

[37] Stephen Adolph, W., Cash Cow in the Tar Pit: Reengineering a Legacy System, IEEE, 1996

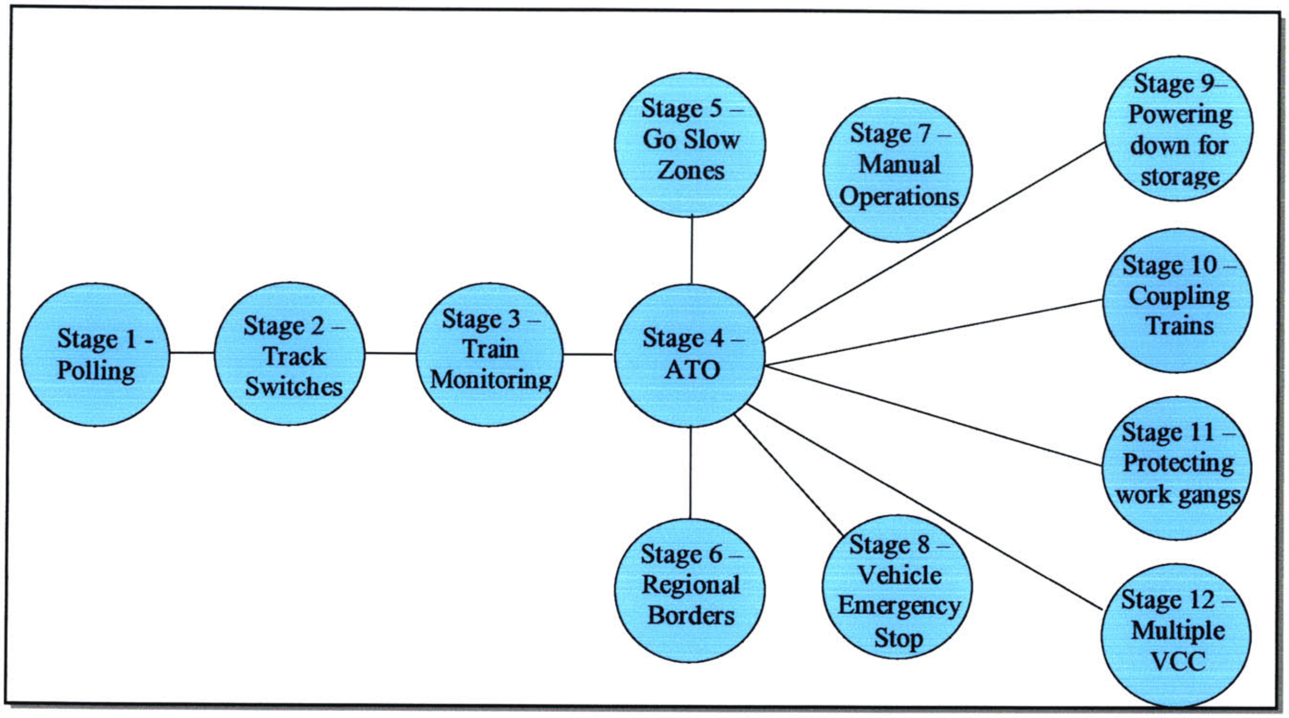


Figure 3-2: Replacement stages for the GA900 replacement[38]

It is obvious that RTS systems are not alone in facing end of life cycle challenges. In the defense and military sector for example the equipment used has to undergo frequent complex and costly system upgrades to be operationally ready[39].

The discussion so far has focused on technological obsolescence. There is the additional aspect of structural, physical and material degradation. The subsystems in the RTS that have been around for say 15 to 30 years may have suffered physical or structural degradation. This structural degradation at times might be irreparable. The physical or structural degradation is to be expected with constantly maintained systems and as a result of time and heavy usage. For example the de-bogie action on a train after a long period could damage the centre pivot because the cyclic nature of loadings on a train can lead to material fatigue. Water penetration in the structure of a viaduct or guideway would cause corrosion of the re-bars and weaken the structure. All these factors need to be considered in the decision of extending the life of a system. The literature also supports this notion that any system that undergoes constant maintenance is subject to system degradation, leaving mature systems whose age may be determined by age or

---

[38] Stephen Adolph, W., Cash Cow in the Tar Pit: Reengineering a Legacy System, IEEE, 1996
[39] Tomlinson J.S, et al, Functional Discovery to Enable Confident Change, INCOSE Conference, 2000

usage with a greater incidence of degradation[40]. How the maintenance regime influences the life span of the system is further elaborated in the next section.

3.1.1 Performance versus Time of RTS Systems

Figure 3-3 below shows the performance of RTS subsystems over time.

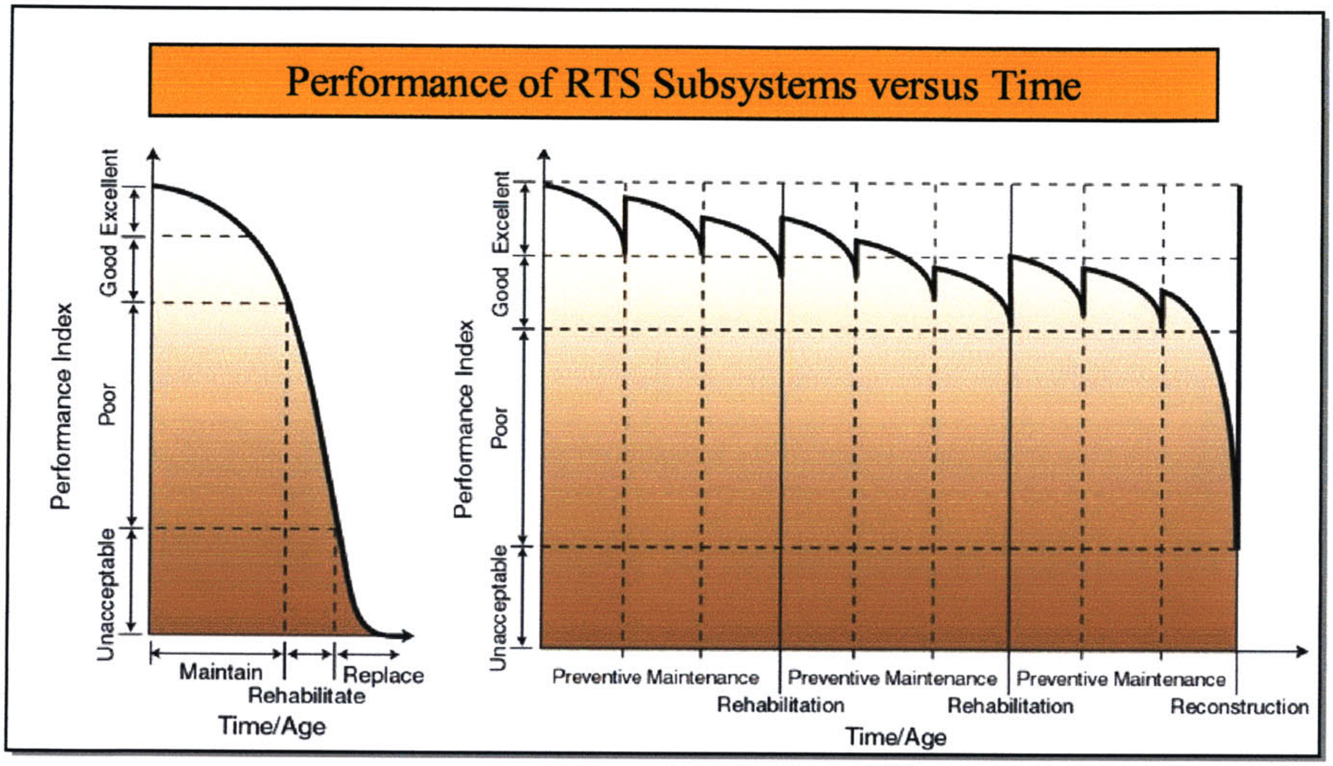


Figure 3-3: Performance versus time of RTS Subsystems[41]

The *Introduction* stage of the RTS subsystem into revenue service is typically followed by excellent performance and minimal maintenance. There would be unforeseen problems during the introduction that may impact performance but these are usually one off issues and are easily rectified. One example of such an unforeseen problem comes from the Integrated and Supervisory Control System (ISCS) on the North East Line Singapore. Given the architecture of the system feeding back all alarms to the Operations and Control Centre (OCC), during the initial stages of testing/operation in 2003 the OCC was overwhelmed by thousands of alarms per day. This was impractical and commanded a huge commitment of resources to deal with the alarms. A fix was finally implemented on the system that entailed the screening of alarms based on seriousness and safety. This fix helped to reduce the frequency of alarms considerably.

---

[40] Prof. Nigel H M Wilson, Transit Management, Fall 2006

[41] Solomon, R et al, Electronic Part Life Cycle Concepts and Obsolescence Forecasting, IEEE Vol. 23 Issue 4, 2000

As an RTS subsystem ages the charts indicate that its performance deteriorates and at specific instances in time, the RTS subsystem undergoes preventive maintenance to restore its performance to an acceptable level. However, it comes to a point in time even with extensive preventive maintenance that the RTS subsystem performance does not meet the required reliability and availability targets. The RTS system is then most likely reconstructed or replaced.

The *Reconstruction* stage of the system is when outdated components are replaced with up to date and reliable components. This phase may also include the refurbishment of systems which entails the re-use of the existing system architecture but with more up to date components.

The *Replace* stage occurs when the performance of the system is poor and beyond reinstatement to original reliability levels. In addition the manufacturers are not supporting these aged products. It is at this point that the systems are migrated over to a new system. One distinct sign of obsolescence is the increased maintenance and part replacement to preserve the system functionality[42].

The point to note with Figure 3-3 is based on the life cycle of a single RTS subsystem. Not all subsystems conform to the various stages presented in Figure 3-3. Some RTS subsystems may suffer early die-out due to component failure. In addition advances in technology and material science could spur the system's march to obsolescence during any phase of the life cycle[43]. In the case of RTS system the system life cycle as a whole represents a very complex and convoluted picture. Apart from the issues of technology obsolescence, material advancements and wear and tear there is also the problem of systems retiring at different clock speeds. Figure 3-4 develops this notion further.

As depicted by the figure, the various components of the RTS retire at various points of other subsystems life cycle. This could represent a challenge in replacing retired systems. If for example the communications system is to be retired, extensive testing needs to be done with the other subsystems to ensure safety and functionality. However in a couple of years, the Signaling subsystem would need to be retired, and the testing would need to be repeated. The potential problems with piecemeal renewal and replacement of these subsystems are:

---

[42] Solomon, R et al, Electronic Part Life Cycle Concepts and Obsolescence Forecasting, IEEE Vol. 23 Issue 4, 2000

[43] Solomon, R et al, Electronic Part Life Cycle Concepts and Obsolescence Forecasting, IEEE Vol. 23 Issue 4, 2000

- What amount of testing would guarantee that a renewed or replaced RTS subsystem is working safely and functioning correctly? Testing and validation are conducted over specific periods and test plans written based on the designers experience but is this a guarantee of safe performance;
- Given the wide and inconsistent life spans of RTS subsystems, there is the issue of technology compatibility. It is a well know and reiterated fact that technology advances rapidly. Technology (software and hardware) used for example with the communications system in Year 1 could have potential interface problems with technology used for the signaling system renewed or replaced in Year 10; and
- The design of renewed or replaced RTS subsystems depends very much on the expertise within the manufacturer. Given human resource dynamics it could be the case that the designers of the communications system in Year 1 have left the manufacturer by the time the Signaling system is renewed or replaced in Year 10. The departure of designers could potentially leave gaps in the manufacturer's knowledge domain and this could translate to far from perfect renewed or replaced RTS subsystems.

Thus subsystem replacement cannot be done strictly on an individual subsystem basis but needs to consider system level factors. A possible strategy would be to try to stretch the life cycles of subsystems to synchronize their retirement to ensure a seamless switchover to a new system while at the same time reducing cost intensive testing. This topic will be further discussed in Chapter 4.

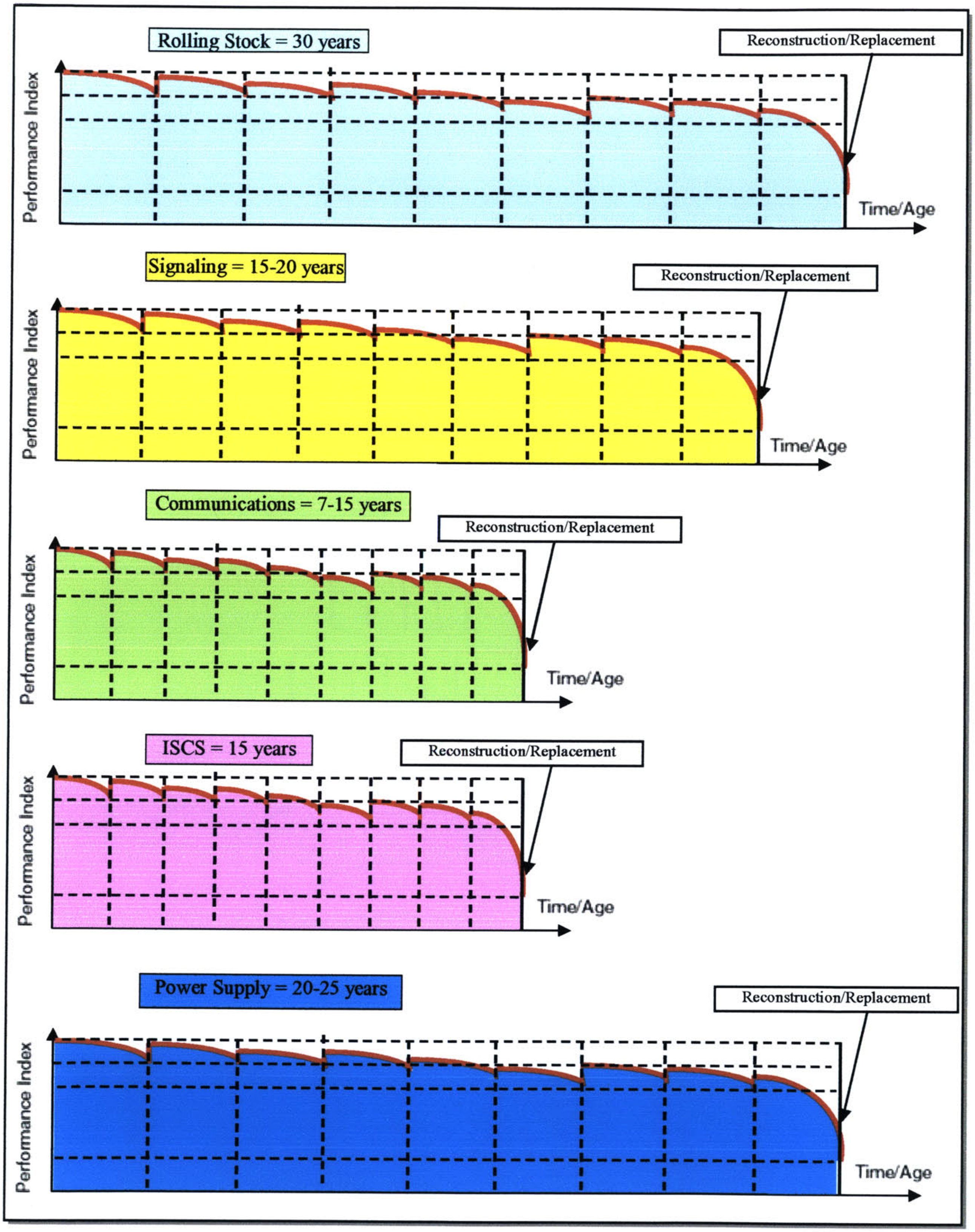


Figure 3-4: Different System Life Cycles for RTS Non-Civil Systems[44]

---

[44] Figures Obtained from LTA Asset Replacement Grant Figures and a study trip to Bombardier Transportation (Pittsburgh) from 11/2/06 to 11/7/06

3.1.2 Interactions of the non-civil RTS subsystems

In Section 2.5, the V development diagram illustrated the various stages of standalone subsystem testing required and finally in marrying all the subsystems together, the amount of testing to ensure proper integration and functionality. It is envisaged that with the renewal or replacement of the RTS subsystems a similar level of testing would be required given the interactions between the non-civil RTS subsystems. Table 3-1 shows the interactions between the various RTS subsystems and highlights that RTS subsystems are not standalone but the replacement of one RTS subsystem also impacts other RTS subsystems. As highlighted in Chapter 2 this inevitably makes the task of renewal or replacement of RTS subsystems more challenging. Testing costs money and time and as a result of these constraints, manufacturers, transit authorities and operators should resist the urge to cut corners and carry out minimal testing. Conversely, without an innate knowledge of the RTS subsystem interfacing, the task of renewal or replacement becomes risky, in particular with safety critical RTS subsystems such as rolling stock and signaling.

Interface Matrix	RS	SIG	HV	LV	ISCS	MMS	OCS	COM	L&E	AFC	TV	FPS	WAGN	LOCO	DEPT	AMS
Rolling Stock (RS)	■	☒	☒	☒	☒	☒	☒	☒			☒	☒		☒	☒	
Signaling/Platform Screen Doors (SIG)	☒	■	☒	☒	☒	☒	☒	☒			☒	☒				
Power Supply –High Voltage (HV)	☒	☒	■		☒	☒	☒				☒	☒		☒	☒	☒
Power Supply – Low Voltage (LV)	☒	☒		■	☒	☒		☒	☒	☒		☒			☒	☒
Integrated Supervisory Control System (ISCS)	☒	☒	☒	☒	■	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒
Maintenance Management System (MMS)	☒	☒	☒	☒	☒	■	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒
Overheard Catenary/ Third Rail Supply (OCS)	☒	☒	☒		☒	☒	■					☒	☒	☒		
Communications (COM)	☒	☒		☒	☒	☒		■	☒	☒		☒		☒	☒	☒
Lifts and Escalators (L&E)				☒	☒	☒		☒	■			☒				
Automatic Fare Collection (AFC)				☒	☒	☒		☒		■		☒				
Tunnel Ventilation & Environmental Control System (TV)	☒	☒	☒		☒	☒					■	☒				
Fire Protection System (FPS)	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	■	☒	☒	☒	☒
Wagon (WAGN)					☒	☒	☒					☒	■	☒		
Service Locomotives (LOCO)	☒		☒		☒	☒	☒	☒				☒	☒	■	☒	
Depot (DEPT)	☒		☒	☒	☒	☒		☒				☒		☒	■	
Access Management System (AMS)			☒	☒	☒	☒		☒				☒				■

Table 3-1: Interface Matrix of the Non-Civil Subsystems (Legend – ☒ represents interface)

3.1.3 Maintenance Strategies and their Influence on the Life Cycle of the RTS

While the various subsystems in the RTS system have different life spans, the maintenance strategies that are adopted also play a part in the expected life spans of the subsystems. The two governing factors of maintenance are cost and impact of failure on operations. Cost here refers to the component cost and the cost of maintenance while impact refers to the system availability and reliability should a subsystem fail. The trade-off between the cost and impact is weighed to assess the best maintenance strategy. Figure 3-5 provides an overview of this classification.

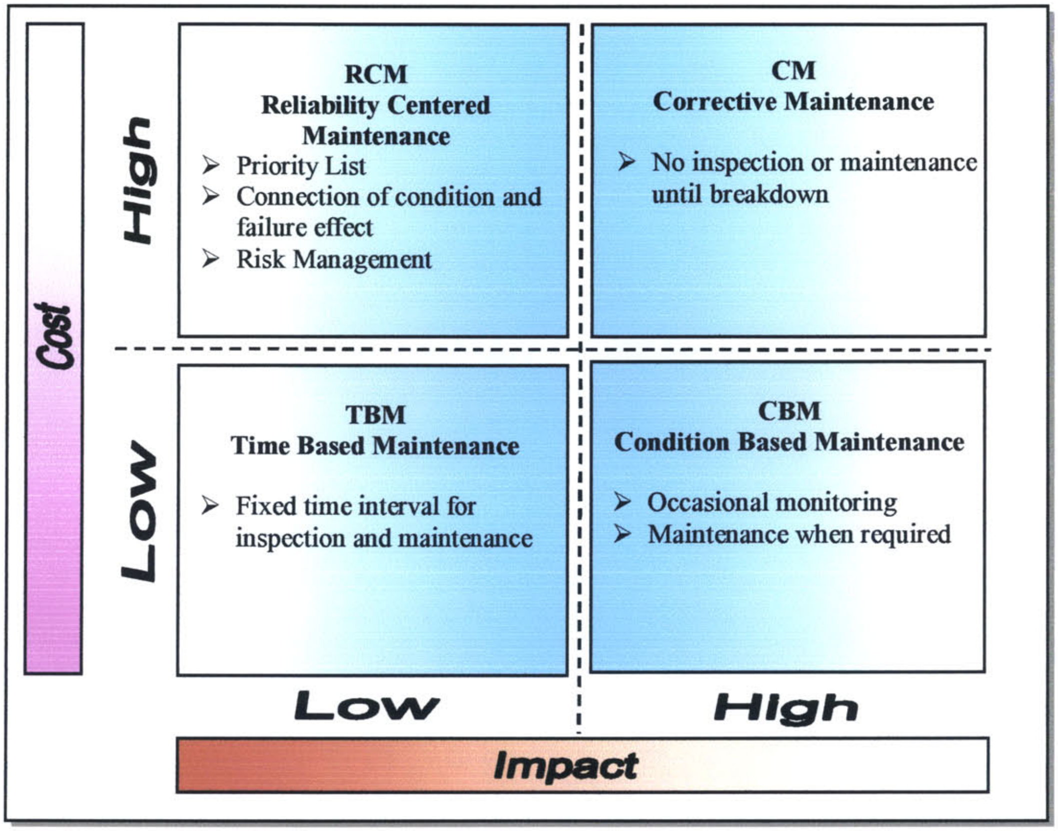


Figure 3-5: Classification of Maintenance Strategies (Diagram modified)[45]

In Time based maintenance which is essentially preventive maintenance, the costs compared to other types of maintenance are low. In addition, the probability of failure and hence the impact on Operations is low given the strict schedule of maintenance that is carried out.

For Condition Based Maintenance (CBM), the cost of this type of maintenance is also low but the probability of failure of subsystems and its corresponding impact on Operations is

---

[45] Schneider, J. et al, Asset Management Techniques, 15th PSCC, Liege, 22-26 August 2006

high. In this case these systems are occasionally monitored and maintenance administered as and when required.

Reliability Centered Maintenance (RCM) which relies on the constant monitoring of component state and the use of predictive analysis (failure modes) to optimize maintenance coupled with risk management is likely to result in a costly maintenance regime. Given the close scrutiny of the subsystem performance, the probability of a system failure is low and thus does pose great risk for Operations.

Corrective Maintenance, in which subsystems are maintained only based on failure, is costly and most disruptive to Operations. It is very rare that operators adopt this regime except for infrequent and unforeseeable failures that occur.

Based on the literature reviewed, there has not been any correlation done on maintenance strategy and the envisaged life span of an asset/system. Nevertheless, based on logic and the author's experience, it would seem that greatest asset life would result from the following ranked order of maintenance strategies:

- Time Based Maintenance or Preventive Maintenance (PM)
- Reliability Centered Maintenance
- Condition Based Maintenance
- Corrective Maintenance (CM)

It is reasonable to assume that the type of maintenance strategies does indeed play a part in the expected life of the system/component.

3.1.4 Disruptive Technologies in the RTS

Christensen[46] lays out a framework for identifying how new technologies can cause discontinuous or disruptive changes in a market by attacking the existing technology from below. Disruptive technology is "cheaper, smaller, simpler and more convenient to use" than sustaining technology. The first plot in Figure 3-6 shows the normal technology development process with the various revisions of Technology 1, 2 and 3. However, the second plot in Figure 3-6 shows that a disruption in an existing technology could occur anytime within the technology life span. With a technology disruption, Technology 2 forces the early retirement of Technology 1 and takes over at this time from Technology 1.

Disruptive technologies are a reality in the rapid system context, with some examples being moving block signalling displacing fixed block signalling, Insulated Gate Bipolar Transistor (IGBT) technology displacing Gate Turn-off Thyristors (GTO) technology and a few years ago contactless smart card (CSC) technology replacing magnetic stripe tickets. As long as an incumbent technology has deficiencies, the process of innovation will kick in and a disruptive technology will evolve to address these inefficiencies. Therefore the transit authority should be aware of this and note the following impacts of disruptive technologies on the rapid transit system.

- Forces the early obsolescence of the incumbent technology resulting in the Original Equipment Manufacturer (OEM) not longer supporting it;
- The premature replacement of RTS subsystems would cause service disruptions and could entail the retraining/recertification of operations and maintenance staff; and
- It affects the overall business plan and cost benefit assessment (CBA) of the overall RTS system.

---

[46] Christensen, C. M., The Innovator's Dilemma, Collins Business Essentials, 2005

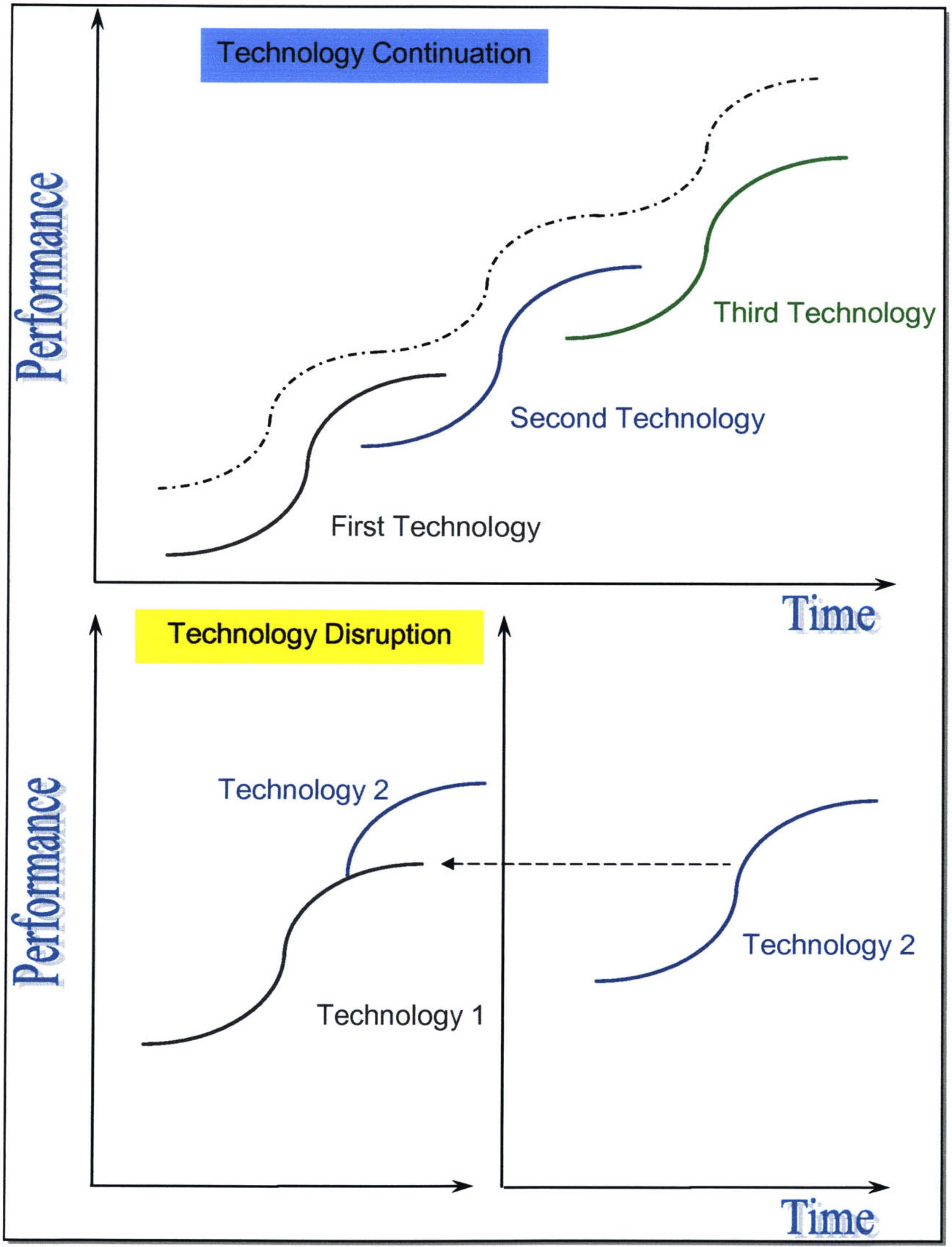


Figure 3-6: Disruptive Technologies Illustrated Using the Technology S Curve[47]

---

[47] Christensen, C.M., The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail, HBS Press, 1997

3.2 Interviews with Industry Experts on End of Life Challenges with RTS systems

In order to achieve a holistic view of the problem, the view of the manufacturer and operator on the problem of end of life of the RTS system was sought. In this respect, a series of interviews were conducted with representatives from Bombardier (manufacturer) during a study trip to their site from 11/2/06 to 11/7/06 and with a representative from the MBTA (operator). The details of the interview are given in Appendix 2 the following sections summarizes the salient points of the interviews.

3.2.1 The Operator's Perspective

In general, both the operator and manufacturer are aware of the end of life cycle challenges. The operator was of the view that their main objective was to maintain their RTS systems in a state of good repair. The state of good repair implies that the system works to a reliable standard and is safe to operate. In the MBTA context, assets in the RTS system are renewed at critical midlife points or replaced at the end of their useful lives[48]. However, according to the operator given the cost and operational impact, these replacements are often delayed by extending the useful life of the RTS subsystem.

The operator also relies on their observations and experience to predict the failure of components and tailor their maintenance regimes together with the manufacturer's recommendations around this. This strategy though is skewed towards the daily/monthly/periodic maintenance of the system and does not specifically address the challenges associated with the system towards the end of its life cycle.

The operator's view is that all the civil systems will remain even after their 50-120 year life span and assessments may be done to evaluate the life expectation of the civil systems. At most the maintenance frequency might be increased for example the patching of the tunnels and ceilings for leaks. The operator was more concerned with technology i.e. non-civil systems given the advancing complexities of these systems. However, the operator felt that the responsibility was with the manufacturer to ensure that their non-civil systems are over designed to meet more stringent future international engineering standards.

---

[48] Prof. Nigel Wilson, Transit Management Lecture, Fall 2006

Mr. Mulhern's view is that end of life cycle challenges while on the MBTA radar screen is not the top priority of the MBTA. In the strategic plan of the MBTA 2000 for example the following are the key goals:

- <u>MBTA Service</u>
  To provide clean, safe and dependable transportation accessible by a wide spectrum of riders regardless of their personal situations, and a clean and safe environment for employees;
- <u>MBTA Infrastructure</u>
  To pursue and maintain a state of good repair through judicious capital investment decisions and management of individual projects in a prudent manner;
- <u>MBTA Financial Condition</u>
  To provide affordable transit for the riding public and fiscally responsible operations for the taxpayers through efficient and effective operations, innovative fare policies and the continuous development of alternative revenue sources;
- <u>MBTA Employee Development</u>
  To recruit, train and retain a talented, qualified, diverse and committed work force and management team that meets the challenges of providing dependable, safe and affordable transportation to a growing customer base in an increasingly technological environment; and
- <u>MBTA Communication</u>
  To develop and implement a marketing campaign to increase the Authority's market share of transportation by focusing on service standards and operating goals and to clearly communicate the various elements of the strategic plan to internal and external audiences.

Mr. Mulhern noted that the MBTA while looking at the bigger picture prioritizes its actions and for now, its focus is on improving its financial standing and expanding its transit network. The issues of end of life cycle challenges do not take center stage and as long as the RTS system is maintained to a state of good repair the operator is content. Mr. Mulhern reiterated that the onus still lies on the manufacturer to either ensure graceful degradation of their systems or to implement fixes in the design to allow the seamless renewal or replacement of RTS subsystems.

3.2.2 The Manufacturer's Perspective

The manufacturer's view was that the quality of manufacture of civil works and the maintenance of both the civil and non-civil works are critical determinants in tackling end of life cycle challenges. For example, in the manufacture of civil works typically poor quality work such as corrosion of re-bars would lead to the early renewal or replacement of the civil system. The manufacturer has done their own internal evaluations which show that RTS systems that they maintain have a longer life expectancy. The Miami-Dade RTS system which is maintained by the Miami-Dade Transit for example is in the process of replacing 12 cars on their RTS system at a cost of $25.5 million which is to be completed by 2008[49]. Whether there is truth to this statement is debatable? While it is acknowledged that the manufacturer knows their system best, many transit authorities/operators choose to maintain their own systems as the labor force exists to carry out the work and this has been a long serving practice. Singapore Mass Rapid Transit (SMRT) for example, carries out the maintenance of their RTS system and to date; there have not been any major grievances on the level and quality of maintenance carried out. With a strong regulatory framework of monitoring and evaluating the maintenance being executed, this would undoubtedly ensure that the RTS system performs to a required level of reliability and availability.

Conversely, it is also a question of the level of confidence and skill set in maintaining of the RTS system. In Singapore for example, the Bukit Panjang Light Rail Transit system was plagued with problems from the onset of its launch into revenue service in 1999. From problems such as collector shoes dropping off, corrosion, poor termination of terminals in the Gealoc (computer based interlocking) cabinets, holders breaking etc., these engineering incursions led to numerous service disruptions and eradication of public confidence in the system performance. In a major incident of a guide wheel dislodgement, a maintenance audit conducted in 2003 on three aspects, people, procedures and processes found a lack of confidence and skill set of the maintenance staff as a contributing factor to the system's poor performance[50].

---

[49] Libov, C., County set to phase in replacement of 12 Metromover cars, Miami Today, 30 March 2006.

[50] BPLRT Maintenance Audit, 2003 – Authors Leong Kwok Weng, Yao Chuan Sam, John Nuttall, Ajmer Singh Kairon

At present the manufacturer is undertaking a number of contracts (as detailed in Appendix 2) dealing with renewal or replacement of RTS systems. Some of these contracts include;

- Tampa International Airport, Florida APM system – Replacement of vehicles and refurbishment of guide ways;
- Atlanta International Airport System – Replacement of vehicles;
- Neihu Project, Taiwan – Retrofitting of vehicles, re-signaling works, refurbishment of existing line, expansion of the transit network;
- BART Project (completed)- Refurbishment of 450 cars; and
- Orlando Airport – Refurbishment of vehicles.

In this respect, the manufacturers agree that end of life cycle challenges exist and that manufacturers have the knowledge and expertise to deal with them. In terms of R&D investment in ensuring that their RTS subsystems are designed to be more adept in addressing end of life cycle challenges for example, exploring the design architecture to ensure that systems can be renewed or replaced by using a 'plug and play' design, which would remove expensive testing and time, the manufacturer was not convinced of the benefits of addressing the challenge through design. The manufacturer was of the view that even with a 'plug and play' design, testing was still required and to foresee technology advancements 30 years down the road and to incorporate design fixes would be futile and only increase the costs of the RTS subsystem and not make a viable business case.

On the idea of penetrating the market of existing RTS systems by offering maintenance services and hence asset replacement or renewal, the manufacturer was receptive to this idea. For a mature RTS system that is reaching its end of life span, the manufacturer could offer a proposal to undertake the maintenance of the RTS system and the renewal or replacement of the RTS system. The strategy of partaking in the maintenance first before the renewal or replacement, allows the manufacturer time to understand the system operations and stage the asset renewal or replacement. This strategy also allows for better management of risk. With this approach the end of life cycle challenges of RTS systems could be made more attractive to manufacturer's and inevitably allow them to focus more on designing their RTS subsystems to be easily renewed or replaced.

3.3 Conclusion

With respect to both software and hardware systems the following points should be considered when formulating strategies to deal with end of life cycle challenges:

- The management of risk during the renewal or replacement of the RTS systems.

  The thesis has reiterated the importance of risk management in the renewal or replacement of RTS subsystems given that these systems are operational and that the renewal or replacement exercise is undertaken on the fly. It would be catastrophic for any RTS subsystem failure to occur with the system being operated.

- To mitigate the risk of running different systems from different suppliers working together involves detailed simulation and rigorous testing. The other issue is the attainment of intellectual property on proprietary systems to run the simulations and tests.

  The challenge is the management of the labyrinth of interfaces in the RTS system. The fact that the RTS system is comprised of systems from various suppliers makes the task of renewal or replacement more onerous. An approach of managing the different suppliers and removing errors rather than the absence of errors is to run the various RTS subsystems through a barrage of tests. However, with legacy systems, formulating the testing procedures sometimes requires details of the RTS subsystem design and this may be unattainable as a result of Intellectual Property rights.

- The use of extensive testing to verify and validate system functionality, reliability and safety. The use of backward compatible tests to aid in risk reduction.

  In testing the renewed or replaced RTS subsystem, it would be more efficient to conduct backward compatible tests to ensure the system functionality, reliability and safety. This essentially is traversing the processes of the right leg in Figure 2-6.

- The best strategy in the management of end of life cycle challenges is to leave it to the manufacturer as they are the best able to handle the challenge.

  The job is better managed and executed if left to the experts. In addition, it transfers the risk from the operator to the manufacturer. However, this would inevitably involve a price premium. There are also other factors to be considered, for example in the US context a barrier to this approach is the presence of unions. Any unionized labor force would vehemently oppose the transfer of their responsibility and work i.e. outsourcing to a private entity.

- The approach of reuse versus buying new is very cost attractive and adopted by certain Operators.

  As acknowledged by the manufacturer, certain operators choose to refurbish their vehicles as it is cheaper with a cost differential between refurbishment and replacement of each vehicle being $1-3 million dollars. The viability of this approach however, rests on the condition of the vehicles and a detail evaluation of the reused products, for example the carbody, gearboxes, traction motors etc.

- Civil Infrastructure is unlikely to be replaced in particular tunnels, but the best approach to ensure optimal life is a set of good maintenance practices. However, with the running of new vehicles for example, the infrastructure should always have a load assessment carried out.

  A detailed and comprehensive engineering evaluation needs to be carried out to identify potential problems. For example, with the introduction of new rolling stock, a load assessment should be done to ensure that when the new vehicles run on the tracks there are no problems identified within the wheel-rail interface for example.

- In reuse, one of the challenges would be the compliance with current engineering standards. In the case of NFPA-130 which is a fire code, frequent revisions occur which might affect reuse decisions.

  In the case of the refurbishment of the 450 BART vehicles, one major inclusion was the need for a 45 minute fire barrier. Such a requirement did not exist 30 years ago but now requires the inclusion of a fire barrier within the floor structure for compliance. Therefore the requirements of existing standards play a vital part in renewal or replacement decisions.

- In the early stages of design of civil and non-civil systems it is prudent to allow for redundancy to allow for switchover to new systems or the rehabilitation of older systems.

  In RTS system maintenance a few extra vehicles are always purchased over the required number of vehicles to maintain the level of service envisaged. The track alignment is also planned so as to allow for the running of the system in the event of failures such that trains can be turned around of parked in sidings so as to maintain RTS system operations. In this respect, the RTS system should also be designed for asset renewal or replacement. For example in the Tampa International Airport system, the additional guideway helped in the refurbishment exercise for the guideway without impacting service operations.

- Accurate records should be kept of the systems performance throughout its life cycle to better help the decision making process of reusing, rehabilitating or renewing.
  The overall performance of the RTS subsystem should be recorded and detailed records maintained. This helps in ascertaining the problems that the RTS subsystem has faced and thus a more informed decision on renewal or replacement can be made.

Chapter 4: RTS System Strategies towards End of Life Cycle

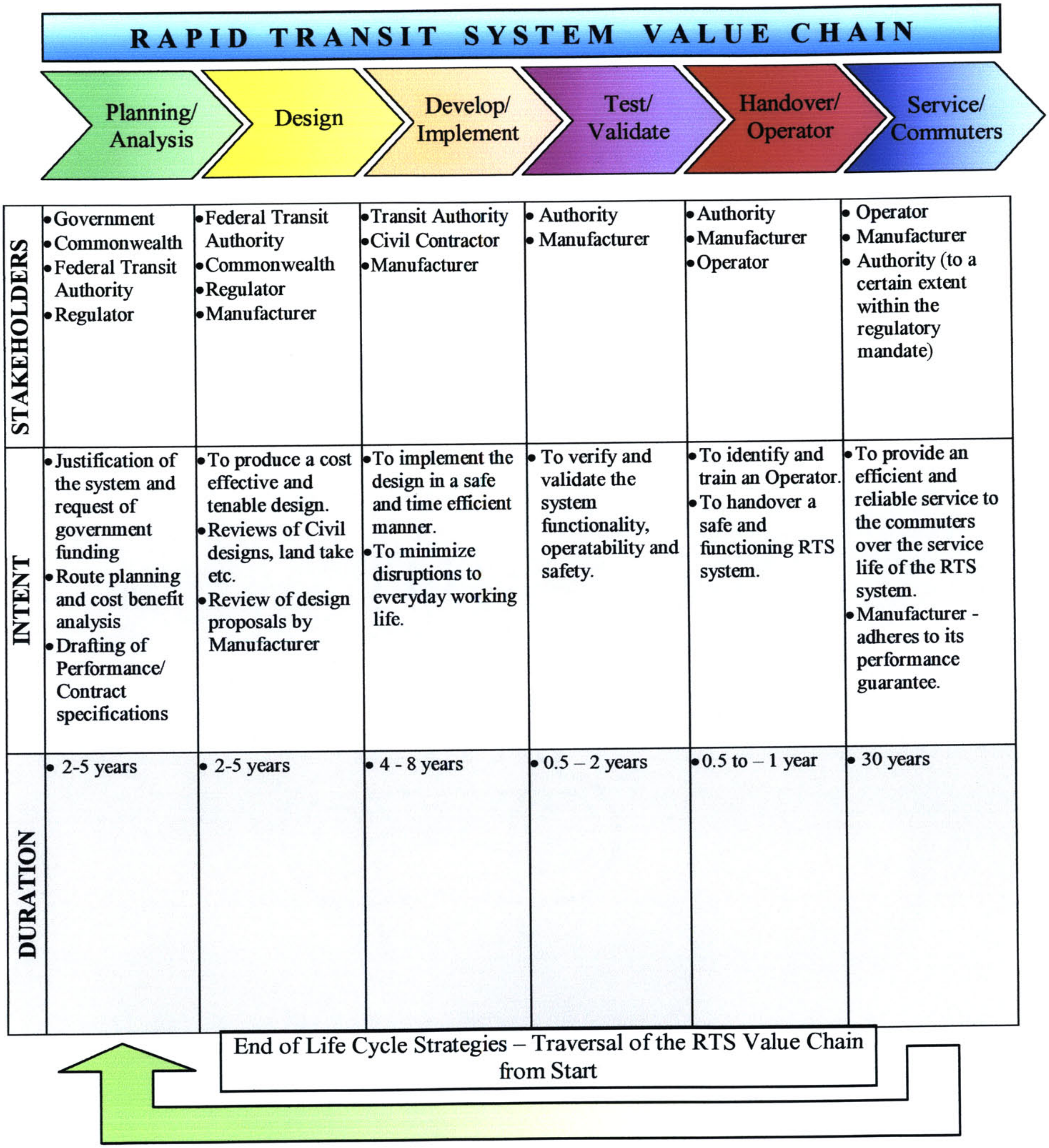
This chapter introduces the RTS value chain and formulates four strategies to deal with end of life cycle challenges (section 4.1). It identifies current practices of agencies in dealing with end of life cycle strategies for their RTS systems (section 4.2, 4.3 and 4.4). System strategies on reuse/recycle/remanufacture, life extension, leasing and public private partnerships are then discussed and their merits identified (section 4.5).

4.1 The Transit Value Chain and Strategy Definition

This chapter describes four strategies in addressing the end of life cycle challenges with RTS systems. Before embarking on a description of the strategies it is worth to define the value chain of a rapid transit system. The value chain in Figure 4-1 shows the delivery of value to the commuters and the responsible organizations.

The value chain shows that three stakeholders play major roles i.e. the federal transit authority/government/commonwealth, the operator and the manufacturer. The role that the transit authority/government/commonwealth plays relates to laying the ground for the realization of the RTS system and its coherent performance after the launching of revenue service. The operator works with the transit authority to deliver the required service levels. The manufacturer's role is the provision of the technological know how and systems to integrate and present a safe and reliable RTS system. By distinguishing further we see that the transit authority/operator monitors the performance of the 'product' while the manufacturer builds; supplies and ensures a safe and reliable 'product'. In this respect, the above three parties play a pivotal role in the formulation of end of life cycle strategies for rapid transit systems.

On the question of responsibility, rather than discuss whose responsibility it is, the following strategies are based on the transit authority/operator bearing responsibility for the end of life cycle challenges. This is logical given the transit authority/operator owns and operates the system. Therefore as the RTS system nears its end of life, the transit authority/operator formulates strategies which eventually see a traversal of the RTS value chain from the start.



	Planning/ Analysis	Design	Develop/ Implement	Test/ Validate	Handover/ Operator	Service/ Commuters
STAKEHOLDERS	• Government • Commonwealth • Federal Transit Authority • Regulator	• Federal Transit Authority • Commonwealth • Regulator • Manufacturer	• Transit Authority • Civil Contractor • Manufacturer	• Authority • Manufacturer	• Authority • Manufacturer • Operator	• Operator • Manufacturer • Authority (to a certain extent within the regulatory mandate)
INTENT	• Justification of the system and request of government funding • Route planning and cost benefit analysis • Drafting of Performance/ Contract specifications	• To produce a cost effective and tenable design. • Reviews of Civil designs, land take etc. • Review of design proposals by Manufacturer	• To implement the design in a safe and time efficient manner. • To minimize disruptions to everyday working life.	• To verify and validate the system functionality, operatability and safety.	• To identify and train an Operator. • To handover a safe and functioning RTS system.	• To provide an efficient and reliable service to the commuters over the service life of the RTS system. • Manufacturer - adheres to its performance guarantee.
DURATION	• 2-5 years	• 2-5 years	• 4 - 8 years	• 0.5 – 2 years	• 0.5 to – 1 year	• 30 years

End of Life Cycle Strategies – Traversal of the RTS Value Chain from Start

Figure 4-1: RTS Value Chain Analysis[51]

---

[51] Duration figures based on the conceptualization and implementation of RTS systems in Singapore

In devising the strategies, a holistic approach of looking at the entire RTS system i.e. a systems approach was adopted. The four strategies discussed in this chapter are:

- Reuse/Remanufacture/Recycle
- Life Extension
- Leasing
- Public Private Partnerships (PPP)

The Reuse/Remanufacture/Recycle entails the renewal of the RTS subsystems without costly replacement of these subsystems. The benefits of this approach are that it minimizes the amount of retraining needed to operate and maintain the subsystems and the testing and validation needed.

The Life Extension strategy focuses on removing the mismatch of life spans of the various RTS subsystems and strives to match the extended life spans of each RTS subsystem into one life span. For example with the Signaling subsystem which has a life span of 15-20 years the challenge would be to stretch its life span to match the life span of Rolling Stock which is 30 years. The benefit of this approach is that it reduces the disruptions to service of having to conduct piecemeal renewals or replacements.

The Leasing strategy is simply leasing the RTS subsystems from the manufacturer. The benefits of this strategy are that the manufacturer assumes the risk of renewal or replacement while at the same time service disruptions are minimized given that the manufacturer is assumed to be experts in their system and hence able to undertake the task of renewal or replacement efficiently and effectively.

The Public Private Partnership strategy focuses on the total transfer of responsibility for RTS subsystems renewal or replacement to the private sector. The benefits of this approach are that the private sector assumes total responsibility of the end of life cycle challenges, the risk is transferred from the transit authority/operator to the private sector and the private sector partakes in the financial contribution towards the renewal or replacement exercise.

Before discussing these strategies in more detail it is prudent first to establish current practices and strategies are of three world wide metro systems i.e. , Boston, Singapore and London and comment on their adequacy.

4.2 Case Study – Boston

The (Massachusetts Bay Transportation Authority) MBTA system is the sixth largest public transportation system in the United States and the largest in the Commonwealth. The MBTA district includes 78 cities and towns, and services 130-plus communities in eastern Massachusetts from Rhode Island to New Hampshire. The MBTA is responsible for providing daily service and maintaining its vehicle fleet for all modes of transportation. The transit system vehicles travel over 30 million miles a year[52]. Please refer to Appendix 3 for the MBTA system map.

As noted in Section 3.2.1, the MBTA is proposing approaching the maintenance and renewal or replacement of their RTS subsystems through a strategy of State of Good Repair. The MBTA maintains a State of Good Repair database which serves two objectives[53]:

- Legislative : The demonstration of ongoing funding needs by conducting an engineering assessment of current assets; and
- Management: The development of a long range capital planning model that ensures project programming under the constrained funding.

The advantage of the SGR database is that it keeps a record of the performance assessments of the RTS subsystems and allows for forward planning of the renewal or replacement of these subsystems. It ensures that the RTS subsystems are performing at an 'ideal' performance. The RTS subsystems are renewed at the mid of their life span or replaced at the end of their life span. The SGR database essentially facilitates this renewal or replacement exercises.

The SGR approach is a hybrid of the reuse/remanufacture/recycle and life extension strategies. The SGR database enables the MBTA to derive maximum life out of their RTS

---

[52] MBTA Strategic Plan – Provided by Mr. Mike Mulhern, MBTA Retirement Fund

[53] Prof. Nigel H M Wilson, Transit Management, Fall 2006

subsystems and while there is always the option of replacement, with cash strapped transit authorities this is rarely a viable option. For now, though this proposal has yet to be implemented as the MBTA does not have the required resources to implement the SGR strategy.

4.3 Case Study – Singapore

In Singapore with the design of RTS systems, the attitude previously was "wait and see" what others are doing in the world. While this is a conservative approach of establishing what RTS systems are and what they aren't, it has nevertheless helped build a Singapore RTS system that is safe and reliable. The establishment of the transportation White Paper in 1996 invoked the mandate to build a world class transport system for the country by 2015. As a result of this mandate, the North East Line (NEL), Bukit Panjang LRT (BPLRT) and Sengkang/Punggol LRT (SPLRT) were built in a short span from the end of the last decade to the early part of this decade.

In this regard, not much work has been done on the end of life planning of the current RTS systems. There is always the argument that given the oldest system is only 19 years of age (launched in 1987), it is premature to discuss this now. However, if it takes 5 years to plan a RTS system, it would take an equal amount of time or longer to rejuvenate, extend the life, and re-evaluate the system.

The Land Transport Authority (LTA) in Singapore however, has in place what is termed asset replacement grants to aid in the obsolescence and replacement of these assets. Table 3-2 lists the eligible operating assets and their corresponding life spans. These asset replacement grants do not entirely assess the end of life cycle strategies of rapid transit systems but provides an impetus to the Operator to replace aging components in the assets to ensure the safety and reliability of the rapid transit system. The Operator submits a Master Replacement Plan (MRP) for eligible Operating Assets to the LTA every year in April according to the LTA budget cycle. The MRP covers assets to be replaced over a three and five year horizon and comprises of the following[54]:

- Asset Items, Remaining Life Span of existing items;

---

[54] Land Transport Authority Replacement Grant – Authored by Leong Kwok Weng, Lim Hock Meng, Lin Min and Ajmer Singh Kairon

- Description specification and expected life span of the new assets;
- Projected expenditure and replacement grant recovery by month;
- Justification for replacing asset based on financial engineering and operational considerations;
- Timeframe for replacements; and
- Assets Items (that are partly funded by government grants and/or replacement grants) which the Operator intends to dispose.

In addition, if there is a premature replacement of assets, the Operator will consult the LTA before submitting the MRP. The Operator is solely in charge of the replacement of these assets under the replacement grant. About two months after the Operator has called a tender to replace these assets, the Operator has to submit to the LTA, technical specifications, budgeted expenditure, projected cash flows and the estimated replacement grant required.

The replacement grant to be disbursed is calculated by the following formula:

Replacement Grant (RP) = Lowest Compliant Tender Price (LCTP) – Historical Cost (HC)

The LCTP is the lowest compliant tender price of the shortlisted tenderers while the historical cost is the amount that was paid in the past to purchase that asset. If the Operator decides to award the tender to a higher price tenderer then they would need to submit an evaluation criteria and appropriate justification to the LTA. The LTA would assess this request and it is up to the Authority's prerogative whether or not to grant this request.

To conclude, the LTA's approach to providing replacement grants helps to address end of life cycle issues based on a Reuse/Replacement/Recycle strategy.

4.4 Case Study – London Underground Limited (LUL)

In the London context, major rail projects are implemented with private sector expertise and financed through Public Private Partnerships (PPP). London Underground is now becoming more of a facilitator/purchaser of transportation systems that meets and services the needs of London rather than a provider. The United Kingdom developed the Private Finance Initiative

(PFI) in 1992 to fund public sector capital projects and service provision[55]. The PPP framework has developed alongside the PFI. The one notable advantage of the PPP framework is that it allows the sharing of project responsibilities and risks between the client and contractor.

Other advantages of the PPP framework are:

- The sharing of development, implementation and management expertise for the project;
- The manufacturers are the experts who know their system best and thus have access to a greater pool of professionals within their organization;
- The ability to implement systems faster and seamlessly thus allowing the commuters to realize the value delivered by these projects sooner;
- Enhanced planning and execution of the projects as again there is ability to mitigate problems or more importantly as a result of the manufacturers experience to avoid problems;
- Project risk transfer to the contractor rather than the client;
- The client now has more free time to concentrate on other transport challenges and not be bogged down by new project implementation;
- It brings to the table private sector capital for project implementation; and
- It delivers greater value of money (VFM) over the life of the projects because the private sector assumes some of the financial risk (and costs) that the public sector would otherwise carry[56].

Therefore with the Government's PPP policy, the private sector is taking responsibility for London Underground's capital investment, operational and network management. Not only is there a severe shortage of capacity on the existing lines, the rolling stock is old and the

---

[55] Harris, N., Railway Operations Module, MSc in Railway Systems Engineering, University of Sheffield, 1998

[56] Shaoul, J., A Financial Appraisal of the London Underground Public-Private Partnership, Public Money and Management, Apr-Jun 2002

infrastructure is in need of considerable investment to ensure a reliable, regular and more frequent service[57].

Thus, in the LUL example we can see that PPP has advantages of being a strategy in the management of end of life cycle challenges with RTS systems. It is clear that the engineering and financial risks are borne by the contractor and at the same time the advantage here is, that the system renewals/rehabilitation is left in the hands of experts to carry out.

The PPP framework in London is set up with LUL (please refer to Appendix 4 for the system map) assuming public control and the network infrastructure and associated staff being transferred to three private sector infrastructure companies known as 'Infracos'. The three Infracos are:

- **B**akerloo, **C**entral, **V**ictoria lines – **BCV** Infraco
- Circle, District, Hammersmith & City, Metropolitan, East London (**S**ub **S**urface **L**ines) – **SSL** Infraco
- **J**ubilee, **N**orthern, **P**iccadilly – **JNP** Infraco

For the BCV and SSL Infraco, Metronet which is made up of a consortium containing Bombardier, Balfour Beatty and Atkins was successful in their bid. Here you have a non-civil systems specialist, a civil infrastructure specialist and a railway consultancy specialist all working together. Each Infraco is given a 30 year contract to operate and maintain their respective lines.

One major responsibility of these Infracos was the maintenance of the existing assets *but more importantly the enhancement, modernization and renewal of these assets according to specified capacity and performance levels*[58]. Metronet modernization and renewals plans for example includes investing £17 billion (US$32.2 billion) during the 30-year contract and has pledged to invest over £2.5 million (US$4.89 million) every working day for the first seven-and-

---

[57] Ross, J., Management Philosophy of the Greater London Authority, Public Money and Management, Oct-Dec 2001.

[58] Meeting with Mr. Chew Tai Chong, President London Underground Projects, Bombardier, London, UK, 31st May 2006

a-half years of its contract. Some of its other commitments in terms of line modernization include[59]:

- 150 stations modernized or refurbished by 2012 ;
- 127 miles of new track; 166 points and crossings renewed in the first 7.5 years ; and
- Comprehensive upgrade of all civil assets – 806 bridges, 2,000-plus structures, 77.5 miles of tunnels, 103 miles of embankments and cuttings and 77.5 miles of track drainage – all in the first 15 years.

To conclude, PPP arrangements to date seem to be a successful strategy in addressing end of life cycle challenges of rapid transit system. However, these are still early days in the PPP arrangement for LUL and its effectiveness in addressing end of life challenges stills needs to be monitored and overall success in the long term evaluated. As with any strategy, the PPP arrangement has its disadvantages as well and this will be discussed in a later section.

4.5 System Strategies to Address End of Life Cycle Challenges

In formulating the end of life cycle strategies both the civil and non-civil renewals and replacements are treated separately. The reason being the wide gap in life spans would make it unfeasible to incorporate civil strategies with non-civil strategies.

As emphasized by the industry experts based on the interviews conducted (refer to chapter 3, section 3.2 onwards) civil systems should last or exceed its life span of 50 to 120 years, as long as the infrastructure is built based on quality standards/specifications and undergoes the required maintenance.

If the civil systems reach their end of life cycle, for the bridges/viaducts the rebuilding is straightforward. The real impact though is to the already existing railway operations. These impacts are minimized by having redundant routes built in the network or supplementing the service with buses. The assessment of this impact demands a separate study on its feasibility and execution plan.

---

[59] http://www.metronetrail.com

On the tunnel reaching its life span of 120 years, based on the LUL experience (in operation since 1863[60]) there is nothing much that can be done apart from engineering assessments to extend the life of the tunnel (please refer to Appendix 4 for a detail listing of all the LUL lines and years in operation). However, it has been suggested by some industry experts that we use a larger tunnel boring machine (TBM) with a diameter greater than the existing tunnel dimensions and re-bore through the old tunnel[61]. In the LUL case for example the minimum tunnel diameter is 3.56m (11ft 8.25in) clearly it would make sense to re-bore which would increase the tunnel size and increase the passenger carrying capacity of the lines. The LUL optimizes the size of their rolling stock by using smaller wheels to increase the internal size of the cars thus increasing their carrying capacity as a result of the tunnel diameter constraint.

Current Tunnel Boring Machine (TBM) technology allows for tunnels of 9.5m to be bored. The most and common form of this technology is the Earth Pressure Balance Machine (EPBM) which is relatively safe given that it maintains a constant pressure on the tunnel face during boring which prevents cave-ins or ground settlement. The most recent project completed for example in Spain, Metro Sur, saw a 41 km long line built in only 29 months. Most sections (a total of 27 km) were excavated with five 9.5 m diameter TBMs, the rest being built by cut-and-cover. All stations were built by cut-and-cover and have a similar and very spacious appearance[62]. The main reason for the short construction period was a result of TBM technology allowing 9.5m tunnels being built at a time. This allowed two separated lines to be built in the same tunnel after that. In fact, the Metro Sur Project showed that EPBM is a much safer method in tunneling compared to other open face tunneling like the New Austrian Tunnel Method (NATM) and sprayed concrete lining (SCL)[63]. An illustration given on EPBM is given in the Figure 4-2.

---

[60] http://en.wikipedia.org/wiki/London_Underground

[61] Meeting with Associate Professor Felix Schmid, Railway Systems Engineering, University of Birmingham, Birmingham, United Kingdom, 3rd June 2006

[62] http://urbanrail.net/eu/mad/linea12.htm

[63] Bennett, S., Madrid confirms its low-cost approach - Rapid Transit, International Railway Journal, May 2003

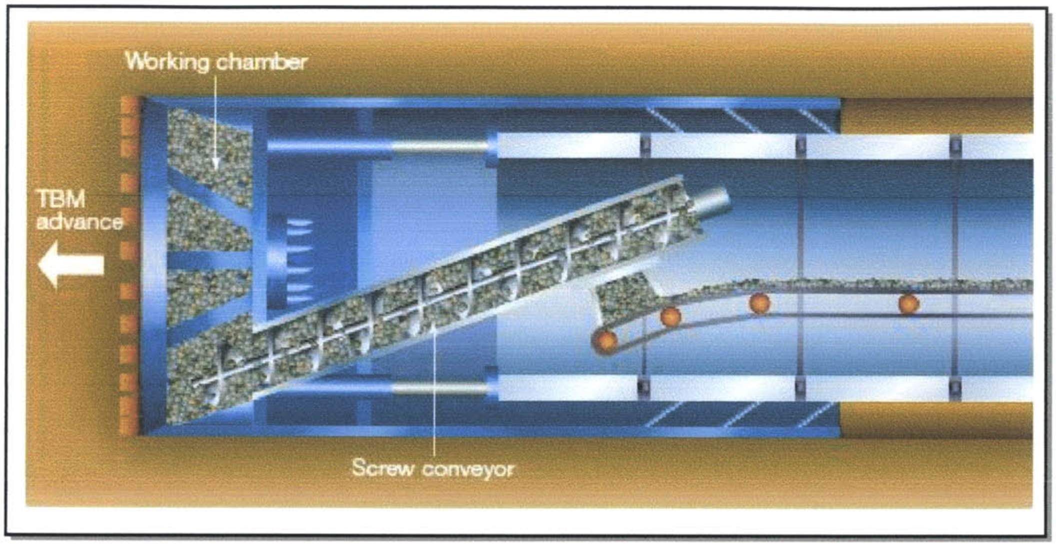


Figure 4-2: Simplified EPBM Scheme[64]

Therefore, with EPBM it does lend an option of re-boring as showed in the figure below. With the boring of the new tunnel, one tunnel is sacrificed while the other older tunnel can be utilized as a means for emergency egress. This tunnel set-up is similar to what exists on the Channel Tunnel Rail Link (CTRL) in the United Kingdom.

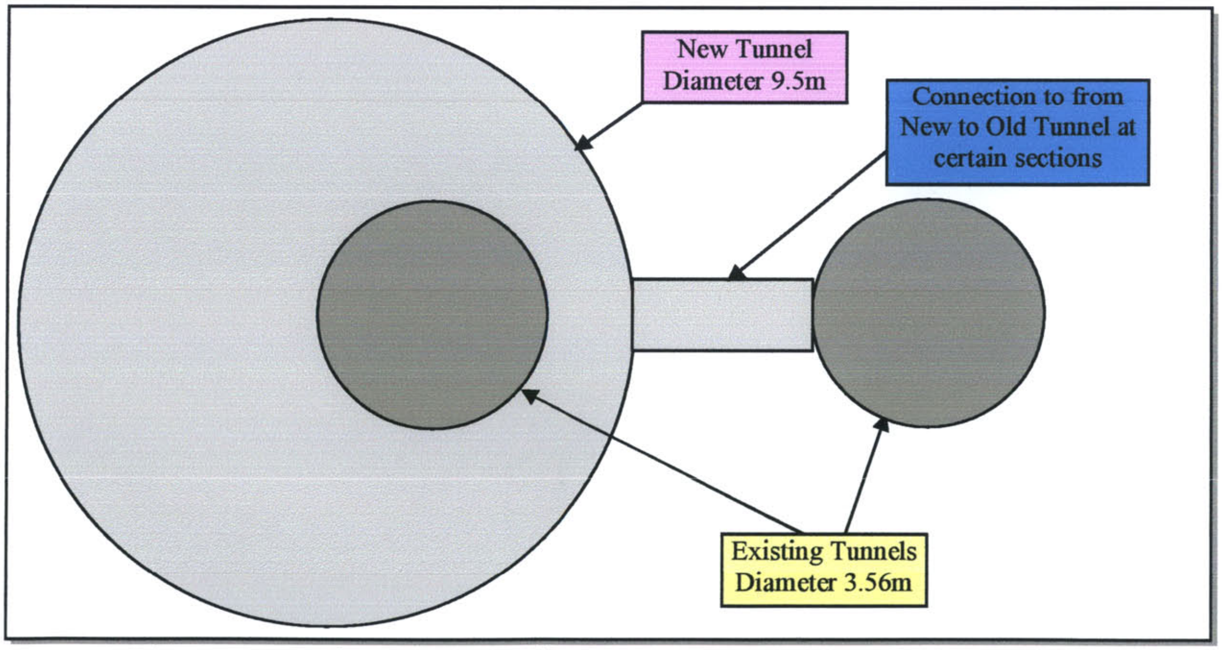


Figure 4-3: Re-boring scheme for New Tunnels over Existing Tunnels

---

[64] Qiu, L.F., Soil Conditioning for modern EPBM Drives, Tunnels & Tunneling, December 2004

What is represented in Figure 4-3 is an illustration of what can be done. It is an expensive option and again needs careful assessment in terms of its cost, impact to operations and civil engineering feasibility.

In addition the advantages and disadvantages of re-boring a new tunnel are;

Advantages

- By re-boring through existing tunnels, the time taken would be less (less earth removal) and in place you would have a new infrastructure that could last another 120 years or more;
- Tunnels and new non-civil infrastructure are built to current and future engineering and safety standards;
- This approach allows a revisiting of existing line design, capacity and features; and
- Given the advancements of technology in the future a tunnel life span of more than 120 years maybe obtainable.

Disadvantages

- Existing non-civil systems needs to be replaced in total and hence the timing of asset renewal with new tunnel construction needs to be well coordinated;
- Impacts existing train operations and would lead to public outcry if not properly managed;

The focus of the following sections is on the non-civil systems given their shorter life spans relative to the civil infrastructure. The strategies to deal with these systems are given in the following sections.

4.5.1 Reuse/Remanufacture/Recycle

Reuse/Remanufacture/Recycle is a life extension strategy but without the complete replacement of the system. For the purpose of simplicity all these terms will be amalgamated to just mean Reuse. Reuse entails reengineering of the RTS system to extend its life span. In life extension the intention is to extend and synchronize the life spans of each of the subsystems. In reusability, the reengineering is defined as examination and alteration of subject systems to reconstitute them in a new form and the subsequent implementation of the new form[65].

One example of reengineering was with the BART (Bay Area Rapid Transit) rolling stock. A total of 450 cars on the BART system were reengineered and only the stainless steel body carcass was reused (please refer to Appendix A3, section E). While reengineering reaps costs savings it also provides engineers an avenue to see where the design could be enhanced and optimized to improve its functionality and performance. In addition, it allows for an increase in understanding of the system or product itself[66]. With an intimate knowledge of the system, engineers are better equipped to innovate and be creative in their new designs. In the innovation classes, the engineers are defined as lead users where lead users are the ones that benefit from the innovation/improvement. This is different from an innovation from a manufacturer which is often the case with new systems where the innovation is a result of the manufacturer expecting to benefit by selling it. The two concepts are defined in the bullets below[67];

- An innovation is a **USER innovation** when the developer expects to benefit by USING it;
- An innovation is a **MANUFACTURER innovation** when the developer expects to benefit by SELLING it.

The table below summarizes the value of reuse and the potential costs of reusing in a rapid transit system. Apart from costs the value that reuse brings includes decreased technological risk, faster development as the designers are not starting from scratch and higher reliability given the innate knowledge of the previous system. Some of the costs or tradeoffs of reuse include lower performance, quality and slower development or adoption of new technology.

---

[65] Chikofsky E.J. and Cross H.H.J, Reverse Engineering and Design Recovery: A Taxonomy, IEEE, January 1990

[66] Sage, A.P., Systems Engineering and Systems Management for Reengineering, Journal of Systems Software, 30:3-25, 1995

[67] Prof. Eric Von Hippel, SDM Lecture on Innovation in the Marketplace, Spring 2006

VALUE	COST
Higher Reliability	Lower System Performance
Decreased Technological Risk	Lower Quality
Accelerated Development	Slower Development/Adoption of New Technology
Lower Cost	Weaker Brand Image

Table 4-1: Value and Costs of Reuse[68]

Reuse is a combination of both forward engineering and reverse engineering. Forward engineering is the traditional process of moving from high-level abstractions and logical implementation-independent designs to the physical implementation of a system. Essentially, forward engineering follows a sequence of going from requirements through designing and implementation. Reverse engineering is the process of analyzing a subject system to identify the system's components and their interrelationships; and to create representation so of the system in another form or at a higher level of abstraction. Reverse engineering often involves an existing functional system as its subject, and this is not a requirement[69].

---

[68] SDM Lecture on Legacy Systems and Reusability by Professor Chris Magee, Fall 2006

[69] Chikofsky E.J. and Cross H.H.J, Reverse Engineering and Design Recovery: A Taxonomy, IEEE, January 1990

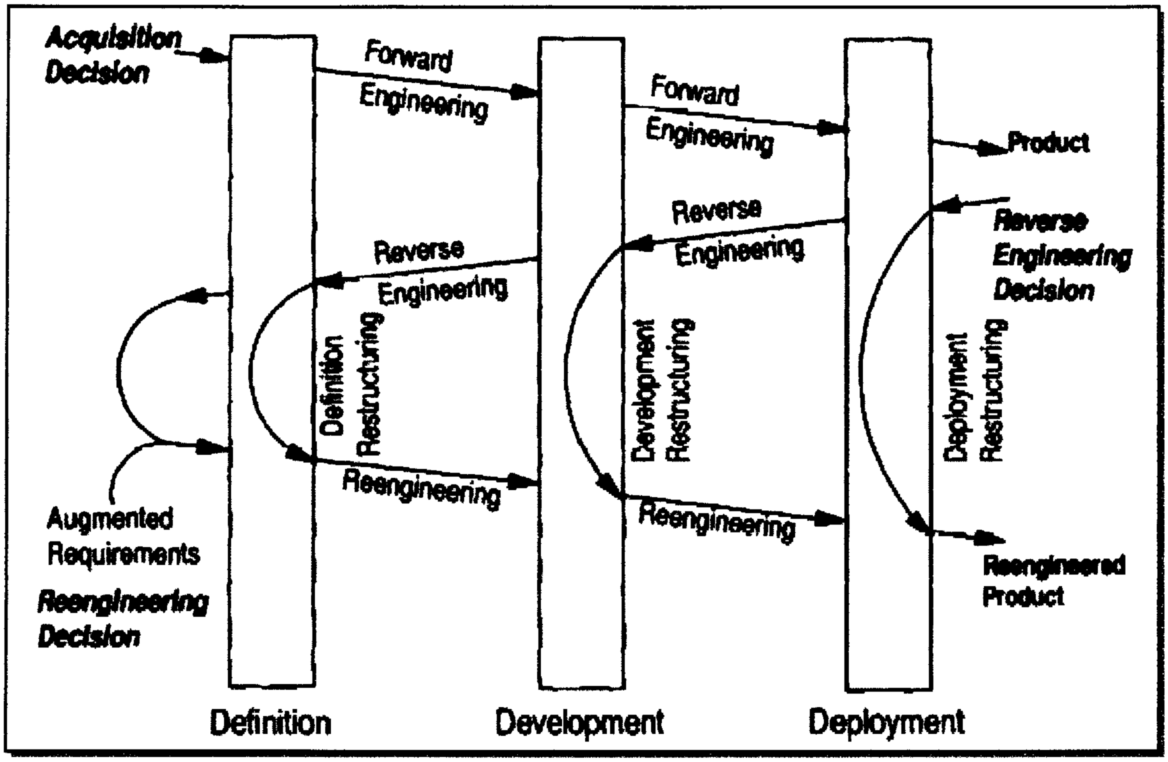


Figure 4-4: The Different Stages of Reuse[70]

Figure 4-4 shows that in the context of forward engineering, a product is developed based on a set of requirements which are focused on the product delivery of value to the customer. Reengineering of a product works in the reverse where the completed product is modified based on an augmented set of conditions. This augmented set of conditions could be a result of the completed product deficiencies. The completed product is then reverse engineered to meet or fulfill this additional set of conditions to address these deficiencies.

It should be noted that reengineering is a process which introduces new functionality and modifications to the system. For example in the GA900 replacement in Figure 3-2, the signaling software was modified such that any changes made to conditions within the software was automatically updated to other parts of the software that used this condition. This represented additional functionality and saved the user maintenance time of having to update other areas of the software with this new condition.

Other considerations that should be taken onboard when making reuse decisions are:

---

[70] Sage, A.P., Systems Engineering and Systems Management for Reengineering, Journal of Systems Software, 30:3-25, 1995

- Core Knowledge: Does core knowledge (of the potential area for reuse) still reside in your enterprise or the manufacturer? If no one knows how the subsystem works the other subsystems with which it interfaces than the reuse strategy can be extremely risky.
- Functionality: Are additional tests needed to fully verify functionality in the proposed environment? Many a time there are additional tests that need to be carried out and the extent and complexity of these tests can be daunting and costly.
- Plants, Equipment and Tools: Can reuse occur without significant additional capital investments for changes/updates?
- Maintenance and Operation: Lifetime costs of training and overcoming organizational inertia are often forgotten.
- Supplier Plans: Does proposed reuse assume indefinite supply?
- Aim: Are there different areas of the system more appropriate for reuse?

Table 4.1 noted the advantage of lower cost and it would be apt to discuss this further in terms of total system value.

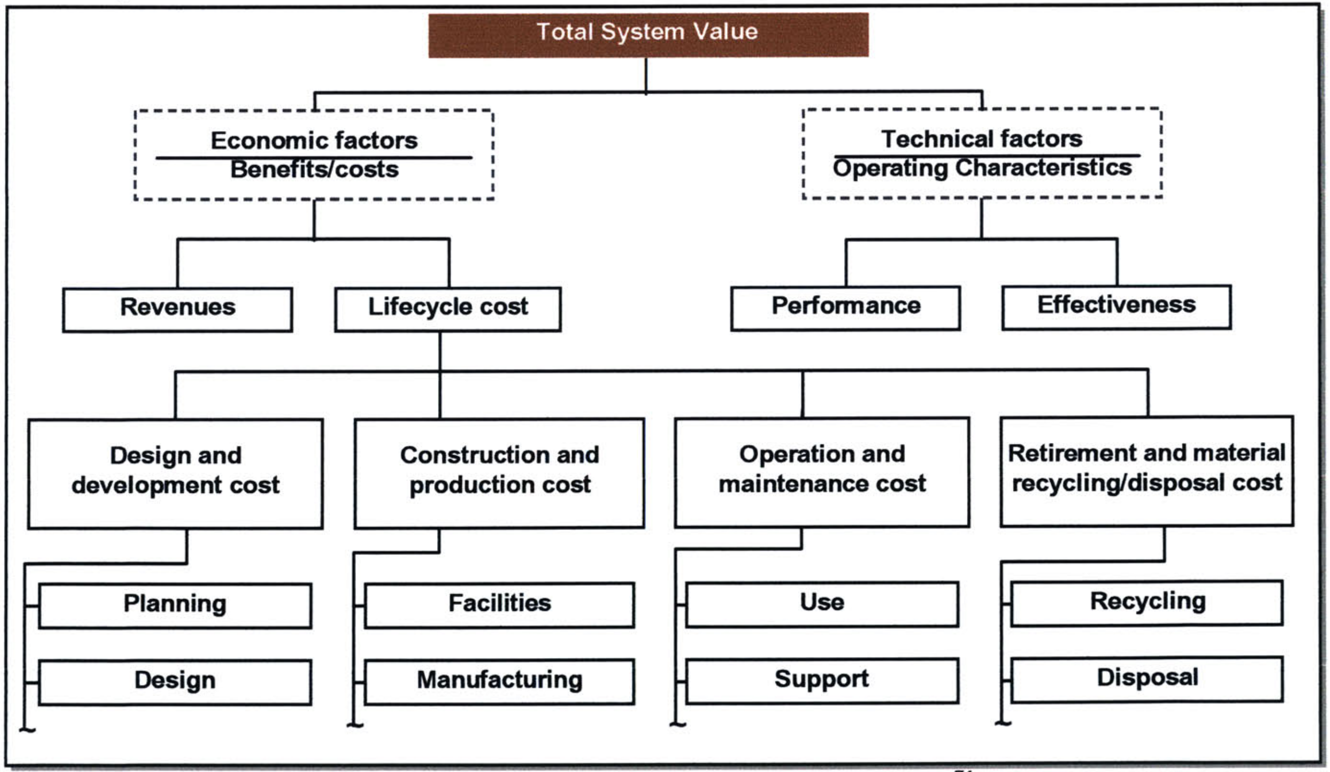


Figure 4-5: Breakdown of total system value[71]

---

[71] Blanchard, B.S. and Fabrycky, W.J., Systems Engineering and Analysis, Prentice Hall, 1998

In terms of total system value for an RTS system with reuse you eliminate the costs of material/recycling and disposal. The operation and maintenance cost with reuse would be status quo. The design/development and construction/production costs differ from building an entirely new system from scratch but would definitely be cheaper than implementing a brand new system. Therefore, in summary with reuse, the total system value would remain the same or be enhanced and is very much dependent on the advancement of technology used in the reuse operation.

To conclude the reuse/remanufacture/recycle strategy is viable to address the end of life cycle challenges of rapid transit systems. Given the huge capital investments of RTS systems, rather than discard parts of the system in entirety, it makes good economic and technical sense to try to salvage and reuse the existing technology. Moreover, this strategy is proven and is practiced by RTS Transit authorities/operators.

4.5.2 Life Extension

Life Extension strategies over a predefined period of time depends on a variety of factors. Table 4-1 lists considerations/factors that need to be taken into account in the life extension of the various subsystems in the RTS. As discussed in Chapter 2, a possible strategy would be to try to stretch the life cycles of subsystems to synchronize their retirement to ensure a seamless switchover to a new system while at the same time reducing iterative cost intensive testing. For example, the signaling system with a life span of 15-20 years could have its life stretched to coincide with the rolling stock life span of 20 - 30 years. This strategy acknowledges that the various subsystems on the RTS need replacement but rather than do it at one subsystem at time which can be disruptive to operations the aim here is to synchronize the life spans of all the various sub-systems to their maximum life span.

This exercise is costly and the benefits need to be weighed against replacing or renewing RTS subsystems as and when they expire for example the cost of testing the entire RTS system as and when new subsystems come on board. There is also the risk associated with life extension strategies primarily with safety, performance and technology obsolescence and these risks need to be considered as uncertainties are inevitably going to drive the project value up.

There are several advantages to life extension apart from cost. Firstly, it allows the knowledge and expertise contained within the RTS to be preserved. Secondly, by not replacing the subsystems as and when they expire, it reduces the risk involved with constructing and implementing new subsystems. By eliminating the need to introduce new subsystem, engineers can focus on extending the life of the system and solving problems that are current with the system instead of focusing on the new issues created with the introduction of a new subsystem[72]. Thirdly, life extension preserves the functionality of the original subsystem and system as a whole.

Life extension strategies provide a viable strategy in the management of end of life cycle challenges. However, much of life extension depends on the actual condition of the RTS which translates to the quality of maintenance that is administered to the system. If a system is maintain to a pedigree set of standards, life extension becomes a true possibility.

---

[72] Stephen Adolph, W., Cash Cow in the Tar Pit: Reengineering a Legacy System, IEEE, 1996

Electrical and Mechanical

Description	Estimated Life Span (years)	Life Extendable? (Y/N)	Critical Factors to be Considered for Life Extension
Train (Rolling Stock)	20 -30	Y	• Components of the propulsion equipment for example, motors gearboxes would need to be overhauled and auxiliary equipment like batteries need to be replaced. Conformance to up to date standards need to be assessed. For example, NFPA-130 states that batteries need to maintain lighting and ventilation for 60 minutes in their recent update. • The chassis and structure needs to be checked in detail (corrosion or cracks) and Finite Element Method (FEM) analysis done based on new loadings (with new equipment) and life extension span. Wear and tear of interior fittings. • Supplier check to validate that OEM's are still supplying parts and for how long more in the future. • Detailed maintenance records need to be kept to ascertain the general health to aid in the life extension decision. • Maintenance periodicity and procedures might need to be reviewed after the life extension.
Permanent Way Vehicles (Track Maintenance Equipment)	15-25	Y	• Same factors as above. • General health of on-board measurement systems, error drifts of measurement equipment on the multi-function vehicles (MFV), grinding accuracy and speed of the rail grinding vehicles (RGV) etc.
Power Supply (Equipment and Cabling)	20-25	Y	• Efficiency of switchboard transformers, inverters in terms power losses, EMC/EMI standards, RoHS. • Effectiveness of electrical relays, problems with oxidizing contacts and pitting of contacts after long service. • General health of OCS (cable tensioning, corrosion, cracks, wear and tear) and third rail supply (ceramic insulation, corrosion, cracks, wear and tear). • Cable health and conformance to current and future fire standards. • Supplier check to validate that OEM's are still supplying parts and for how long more in the future. • Detailed maintenance records need to be kept to ascertain the general health to aid in the life extension decision. • Maintenance periodicity and procedures might need to be reviewed after the life extension.
Supervisory Control System (SCS)	15	Y	• Ability of the SCS system to take on future line expansions. • Support of OEM on software upgrades. • Speed and reliability of the SCS system. • Conformance to current network protocol standards.

Electrical and Mechanical

Description	Estimated Life Span (years)	Life Extendable? (Y/N)	Critical Factors to be Considered for Life Extension
Escalator & Lifts	15	Y	• Life extension possible but not really required as the escalators and lifts interfacing to the other subsystems to the RTS is limited.
Environmental Control System	15-30	Y	• Efficiency of heat exchange towers, the cooling towers, chillers and ventilation systems. • Mould growth, corrosion and noise generation. • Supplier check to validate that OEM's are still supplying parts and for how long more in the future. • Detailed maintenance records need to be kept to ascertain the general health to aid in the life extension decision. • Maintenance periodicity and procedures might need to be reviewed after the life extension.
Electrical Service and Fire Protection	15-25	Y	• Supplier check to validate that OEM's are still supplying parts and for how long more in the future. • Detailed maintenance records need to be kept to ascertain the general health to aid in the life extension decision. • Maintenance periodicity and procedures might need to be reviewed after the life extension.
Signaling System	15-30	Y	• Maintainability of the software i.e. is the coding language still available after decades, the ability of the software and hardware to cope with the increase demands of line traffic and the safety criticality aspects of the software are maintained. • The number of patches that have been carried out on the system which would influence its maintainability and reliability. • Supplier check to validate that OEM's are still supplying parts and supporting the software code and for how long more in the future. • Detailed maintenance records need to be kept to ascertain the general health to aid in the life extension decision. • Maintenance periodicity (on train and wayside) and procedures might need to be reviewed after the life extension.

Electrical and Mechanical

Description	Estimated Life Span (years)	Life Extendable? (Y/N)	Critical Factors to be Considered for Life Extension
Platform Screen Doors	20	Y	• General condition of door operating gear, motors and air compression equipment is used. Old doors predominantly used compressed air and the newer versions use electric motors. The motors power by electric motors are more clear cut in evaluation compared to the air actuated doors. • Supplier check to validate that OEM's are still supplying parts and for how long more in the future. • Detailed maintenance records need to be kept to ascertain the general health to aid in the life extension decision. • Maintenance periodicity and procedures might need to be reviewed after the life extension.
Communication System	15-20	Y	• Of major importance the compliance to local codes on air frequencies (radio system) and the backbone network. The communication system is the first to hit end of life cycle and its extension depends on external factors like validity of the system to constantly upgraded standards. • Supplier check to validate that OEM's are still supplying parts and for how long more in the future. • Detailed maintenance records need to be kept to ascertain the general health to aid in the life extension decision. • Maintenance periodicity and procedures might need to be reviewed after the life extension.
Automatic Fare Collection System	7-20	Y	• Life extension possible but not really required as the AFC interfacing to the other subsystems to the RTS is limited.
Depot Workshop Equipment	15-25	Y	• Supplier check to validate that OEM's are still supplying parts and for how long more in the future. • Detailed maintenance records need to be kept to ascertain the general health to aid in the life extension decision. • Maintenance periodicity and procedures might need to be reviewed after the life extension.

Table 4-2: Factors considered in the life extension of the RTS Non-Civil Sub-systems

4.5.3 Leasing

Another viable strategy is for the operator/transit authority to enter into an operating lease agreement with the equipment manufacturer to provide certain components/subsystems of the RTS system, as well as associated support works for the equipment over the tenure of the agreement. In return, the manufacturer receives monthly payments from the operator/authority. Under this arrangement, the manufacturer is responsible for supplying, financing and maintaining the equipment provided. For the operator/transit authority, an operating lease agreement offers the following advantages:

- The manufacturer/contractor assumes responsibility of end of life cycle challenges;
- There is no need to commit high upfront capital expenses;
- There is no need to worry about escalation in the price of spare parts or their availability;
- The manufacturer/contractor is usually able to promise higher reliability and availability figures for equipment that they maintain – at similar or lower costs. This is because the manufacturer knows his equipment best and is thus in the best position to maintain them cost effectively;
- Dependent on the contract structure the manufacturer/contractor is left with the responsibility of ironing out/resolving interface issues with other sub-systems; and
- Leases represent an expense and hence are tax deductible.

Operating leases are a growing trend among operators/transit authorities as it lowers the risks to them while holding the promise of a higher level of service reliability and availability. For example, in the UK, three leasing companies i.e. Angel trains, HSBC rail and Potterbrook Leasing Co, are providing the trains for British Rail; and in Denmark, Potterbrook Leasing is providing trains for the Danish State Railways. The MBTA in Boston currently leases 86 trains on the red line.

Apart from rolling stock, a leasing arrangement could also be adopted for other major non-civil subsystems such as signaling and communications. However, it would be prudent for these non-civil systems to be tied into a single agreement with a single supplier (or consortium) to minimize interfacing problems between different suppliers.

In some countries, the leasing arrangement can be further structured as a cross-border tax lease to allow the manufacturer/contractor (lessor) to reap potential tax benefits. Under such arrangements, the lessor enjoys some tax benefits when he charges depreciation of the asset to offset the income earned by his company. A part of this benefit is passed on to the lessee in the form of reduced lease payments. The level of benefit will vary according to interest rates, duration of the lease, asset type, and tax laws faced by the lessor as well as initial transaction costs.

A key concern with a leasing arrangement is the operators/transit authority's lack of ownership rights to the operating assets. Typically operators/transit authorities are the operating/regulatory body and need to have the assurance of the continued availability of such operating assets, which are necessary for uninterrupted operations of RTS services. One option is to ensure that the leasing agreement provides for the novation [73] of contract to the operator/authority in the eventuality that it has to take over the operation of the system.

4.5.4 Public Private Partnerships (PPP)

Public Private Partnership (PPP) refers to various instruments that involve the manufacturers/private agencies in helping to reduce budgetary/financial commitments on public funds. These could generally have a lesser degree and scope of involvement from the manufacturers/private agencies. For instance, they may apply to only specific components of a project such as rolling stock in RTS systems. In the context of this report and as highlighted in section 4.4 with the London Underground case study, the strategy discussed here would include the RTS system in its entirety. To separate the RTS system into its specific subsystems for a PPP framework would not only convolute the process but lead to the authority managing much of the interfacing challenges between the various manufacturers/private agencies.

The PPP strategy helps address social issues as well. The commitment of the Infracos in London to the betterment of aged assets is publicized to commuters to the detail of dollar value investments over the first seven and a half years. Increasingly, more countries are turning to PPP

---

[73] Novation = Substitution of an old obligation with a new one (www.TheFreeDictionary.com)

as a more viable option for financing infrastructure projects. One example is the Bangkok MRTA's Blue Line[74].

It is evident that the capital injection required for asset renewals or replacement is large. Many transit agencies around the world are operating on heavy subsidies from the Federal government or government. If you take the case of the MBTA for example, based on their statement of expenses and revenues (please refer to Appendix 5) you will see that their finances are in a dilapidated state and the viability of future operations are a growing concern. There exists though, the Capital Maintenance Fund under the implementation of Forward Funding[75], but the size of this fund is limited. At the same time as highlighted in Chapter 1, many transit authorities are more focused on the implementation of new lines to garner more ridership in the hope of increasing their revenue standing as a panacea to their dilapidated finances. This approach may be a flawed strategy and only serves to make matters worst. It results in a viscous cycle when the new assets age and after that require asset enhancement or renewal as well.

Chapters 2 and 3 have highlighted the complexity and life expectancy of technology within the RTS system. One of the main advantages apart from the financial advantage with the PPP strategy, as highlighted in section 4.4, is that it allows the injection of external expertise to help deal with end of life cycle challenges. As seen in section 4.4 the PPP teams are highly skilled and compose of experts from the various disciplines of RTS systems. RTS systems comprise of subsystems that are complex, intricate and intertwined. The risks involved in their rehabilitation or replacement is immense and with PPP arrangements these risks are transferred or shared by the manufacturer/contractor. Table 4.3 highlights some of these risks and the party responsible for the management and mitigation of this risk.

---

[74] The 20km long line was initially awarded to Bangkok Land in 1993 to be developed but was terminated by the government who decided to take control of the project. It decided to fund 80% of project costs (related to civil engineering and construction) using bonds, commercial loans and soft loans. A private party has been concessioned to finance the trains and ancillary equipment, and operate the system as the returns are deemed attractive enough on the operating aspects of the system.

[75] In 2001 the Commonwealth changed the way it financed the MBTA. Under forward funding the MBTA receives 20% of state sales tax revenue plus assessments on the 175 cities and towns the T serves.

Risk Type	Description	Who bears the risk
Design risk	➢ Design of the goods and/or services to meet a specified level of service. (Including redesign costs, risks of obsolescence)	Manufacturer/Contractor to bear design risk.
Construction risk	➢ Construction of facility according to performance specifications and a time schedule. ➢ Sub-contractors/Supplier defaults or bankrupts	Manufacturer/Contractor to bear construction risk. Authority bears the risk of inadequate specifications.
Operating risk	➢ Operating costs, including staffing levels.	Manufacturer/Contractor to bear operating risk.
Demand risk	➢ Ridership risk; ➢ Revenue risk, i.e. fare levels	Authority bears the risk.
Finance risk	➢ Party responsible for debt and debt service, interest rates & currency fluctuations etc.	Manufacturer/Contractor to bear finance risk.
Regulatory risk	➢ Future regulatory changes that could potentially affect the design and operations of the rapid transit system.	Manufacturer/Contractor to bear finance risk.
Integration Risk	➢ To pull all the various non-civil subsystems together such that they work as one entity on the civil infrastructure.	Manufacturer/Contract to bear the risk.

Table 4-3 Risk Sharing in PPP Contracts

There are, however, implications of the PPP arrangements, one of which is higher project costs due to more complex documentation and the lengthy negotiation and procurement process involved. Also, the cost of private funds is generally higher than government funds, with the private sector expecting a reasonable return on their investment that is commensurate with the level of risks undertaken. If the efficiency gains are unable to offset the increase in costs, the additional cost would eventually be borne by commuters in the form of higher fares.

With manufacturers in particular in PPP arrangements, inadequate specifications of the project could compound to expected construction cost risk. Inefficiencies in the management of the construction contract can make it easy for contractors to inflate costs and not appear to be responsible for these increases. There is the risk that contractors may systematically underestimate the costs involved. Lower costs increases the rates of return and hence make it more likely that projects will be undertaken. Once large infrastructure projects are started it becomes difficult to abandon them completely.[76]

In a survey conducted, it was suggested that infrastructure costs are underestimated in 90 percent of transport projects and that the actual costs are on average 28% higher than estimated. This figure rises to 34 percent for fixed-link (major bridge and tunnel) projects and 45 percent for rail projects and is around 20 percent for road projects[77].

Therefore to conclude, the PPP arrangement could represent a viable option of handing end of life cycle challenges. However, PPP arrangements also present risks in particular with the contract management and the validity of costs that are quoted. In this respect, the advantages and disadvantages of this arrangement should be carefully weighed before a decision is made.

---

[76] Vickerman, R., The Regional Effects of Experience with the Private Finance of Transport Infrastructure, 43rd Congress of European Regional Science Association, August 2003

[77] Flyvbjerg, B., et al, Underestimating costs in public works: errors or lies?, Journal of the American Planning Association, Vol. 68, 2002

Chapter 5: Conclusion

No transit system can meet the "ideal" system condition
We can make more effective decisions
We can optimize our investments

Professor Nigel H M Wilson,
ESD227J Transit Management, Fall 2006

The thesis has formulated strategies for dealing with RTS systems towards the end of their life span. Using experiences of transit authorities, industry experts and the author's experience, several strategies were identified and appraised for their effectiveness in providing a solution to end of life cycle challenges. In this concluding section (section 5.1), the salient points of the thesis are highlighted followed by recommendations for future research (section 5.2).

5.1 Conclusion

The quote above summarizes the intent of this thesis perfectly. In the planning of end of life cycle challenges for RTS systems it must be acknowledged that not one strategy is right and represent a total panacea. The strategies at most allow the transit authority/operator to make more meaningful and informed decisions based on risk and cost amongst many other factors. It allows a transit authority/operator to plan ahead and recognize well in advance the challenges were not only at the implementation of the RTS system but a similar set of challenges waits at the end of life cycle of the RTS system.

A systems approach to the management of RTS systems towards the end of their life cycle needs to include the social, technical and economic aspects. Social in terms of the lack or the proposed changes and its associated implications to general public now and in the future, technical in terms of the complexity, management of the interfaces and scale of the task involved and economic with regards to the huge capital outlay needed.

This thesis has looked into the benefits of RTS systems and the crucial part that they play in a modern city. The fact that the RTS system is an elaborate amalgamation of civil and non-civil subsystems functioning together makes the management of its end of life cycle challenging. The life spans of these various RTS subsystems are different and the mismatch in life cycles of these systems could cause formidable challenges in the future if not address early before the end of life cycle. There are two approaches to dealing with these challenges. The first approach is to address the challenge from a design standpoint where the architecture of the RTS system is designed to allow easy and seamless replacement of subsystems with minimal impact to the operation of the RTS system. The drawback with this approach is that it does not address the challenges for already operating RTS systems. The second approach was to focus on existing RTS systems around the world and to ascertain what could be done when most of the systems are at mid-life or nearing end of life and formulate strategies to address these challenges. This report has focused on the latter approach given that systems at mid-life and near end life are of priority and moreover any lessons that can be learnt from these renewals or replacement exercises could be incorporated into new RTS designs.

Chapter 2 provided in-depth descriptions of the construction, testing and commissioning for the civil and non-civil systems for the North East Line, Singapore which is a fully automated driverless railway. The chapter provided an understanding of the peculiar civil and non-civil systems interfacing together to meet the needs of transporting commuters. The interface diagram for the civil and non-civil systems demonstrated the inherent complexity of the system. The various different life spans of the civil and non-civil systems accentuated the challenges of working with subsystems running at different clock speeds.

The major challenge of commissioning an RTS system is the number of verification and validation tests that need to be carried out. The V-V cycle plot demonstrated the comprehensive testing that an RTS system undergoes during commissioning. On the same note, at end of life when systems are rejuvenated or replaced a similar barrage of tests needs to be undertaken now on a fully operational RTS system.

Before embarking on formulating the strategies, it was apt first to understand why this problem exists and how much work has been done thus far on RTS systems to address these challenges. Chapter 3 defined provided a systematic definition of the problem and how maintenance strategies and disruptive technologies influence the system product life cycle. Unfortunately, the literature search showed that while the life cycle of components/ subsystems was well document and studies into legacy systems were done there was little if any work done with respect to RTS systems. This was worrying but to supplement the literature review further a series of interviews were conducted with industry experts to seek their opinions and personal experience on the topic. This exercise proved far more valuable than the formal literature search. The simple reason being all experiences recounted were from real life and not fictitious or simulated. The industry experts agreed that this was an issue at present based on their dealings but sadly the approach being taken to deal with these challenges was on a piecemeal basis as and when systems expired. According to the experts many of the transit authorities carrying out this renewals or replacement work engage consultants to provide external input.

Therefore the recognition that this is a real problem and the lack of work done to address this challenge provides further impetus for the academic world or transit authorities themselves to start investigating these challenges and coming up with solutions.

Three case study examples were given one from the Boston metro, Singapore metro and the London Underground metro on the management of end of life cycle challenges. The Boston approach is the maintenance of a State of Good Repair database to monitor and assess the performance of the RTS subsystems. The database also helps in the forward planning of RTS subsystem renewal or replacement. However, as explained given the priority and financial standing of the operator, this database is essentially a manner of deciding which RTS subsystems life spans and be extended so as to derive the maximum value from them. This however, is done at the risk of service disruptions and the erosion of commuter confidence.

The Singapore approach of providing asset replacement grants represents an incentive based system for the operator to consider utilizing the funds offered in terms of replacement grants to rejuvenate their system or risk losing these grants. This approach is also flawed in that it advocates piecemeal renewals of the system which could lead to further interface problems down the road. The other argument it that there should not be any need for the Authority to incentivise asset renewals as it is the operator's responsibility and not the Authority's. The use of public funds to aid the renewals program of a private listed company can be contentious and interpreted wrongly.

The LUL approach utilizing a PPP framework given in chapter 4 could represent a viable option in dealing with end of life cycle challenges from a systems perspective. The PPP arrangement addresses the social, technical and economic challenges with end of life cycle. It allows the sharing of the development, implementation and management expertise to deal with such challenges. The groups formed to tackle these issues are multidisciplinary from electrical and mechanical manufacturers, civil contractors and RTS consultants. The most notable advantage is that the project risk is transferred to the contractor rather than the Authority and that the contractor has a stake in the project by the way of their capital injection. However, the PPP framework is still new and its overall effectiveness and efficiency at dealing with end of life cycle challenges needs to be evaluated over the long term. Moreover the PPP framework has its disadvantages like the exorbitant upfront legal costs and opportunities for manufacturers/contractors to seek additional compensation as a result of inadequate specifications.

To summarize, the thesis suggests four strategies to address end of life challenges:

1. Reusability/Remanufacturing/Recycling.
2. Life Extension of the Subsystems such that they match up to allow a big bang replacement rather than on a piecemeal basis.
3. Leasing of equipment that passes the risk of replacement to the contractor.
4. Public-Private Partnerships.

These respective strategies have their advantages and disadvantages. While they have been discussed none of these strategies represent an all encompassing solution. At the same time it is not to say that these strategies won't work but it all depends on the needs, requirements and risk appetite of the various transit authorities. The problem of end of life cycle is real and in fact for the London Heathrow Terminal 5 project, the client has asked for a system context that includes the dismantling and disposing of the system.

The transit authority/operator should look at their RTS system and evaluate the best strategy. It may be the case that one of the above strategies meets their needs or a hybrid of the above strategies. The execution of these strategies is also vital to their success but has not been covered in this report and could form the basis of future work.

5.2 Recommended Future Research

There are several areas that could be further developed to address end of life cycle challenges. The following sections discuss these in more detail.

5.2.1 Assessment of the impacts on existing operations

It was noted in real life equipment change out for the Tampa, Florida and Atlanta systems that much of the work was accomplish as a result of careful planning and execution such that this work would not impinge of the daily operation of the existing system. However, the Tampa and Atlanta systems are smaller in size compared to larger RTS systems around the world. To understand the impacts that such operations would have on peak/off-peak frequencies and ridership a separate study should be carried out to understand and manage any complications.

5.2.2 Risk Management

In any exercise of such scale requires careful risk assessment and management. One manner to manage risk which I propose is to stage or separate risk management over the various cycles of the project. The diagram below further exemplifies this concept.

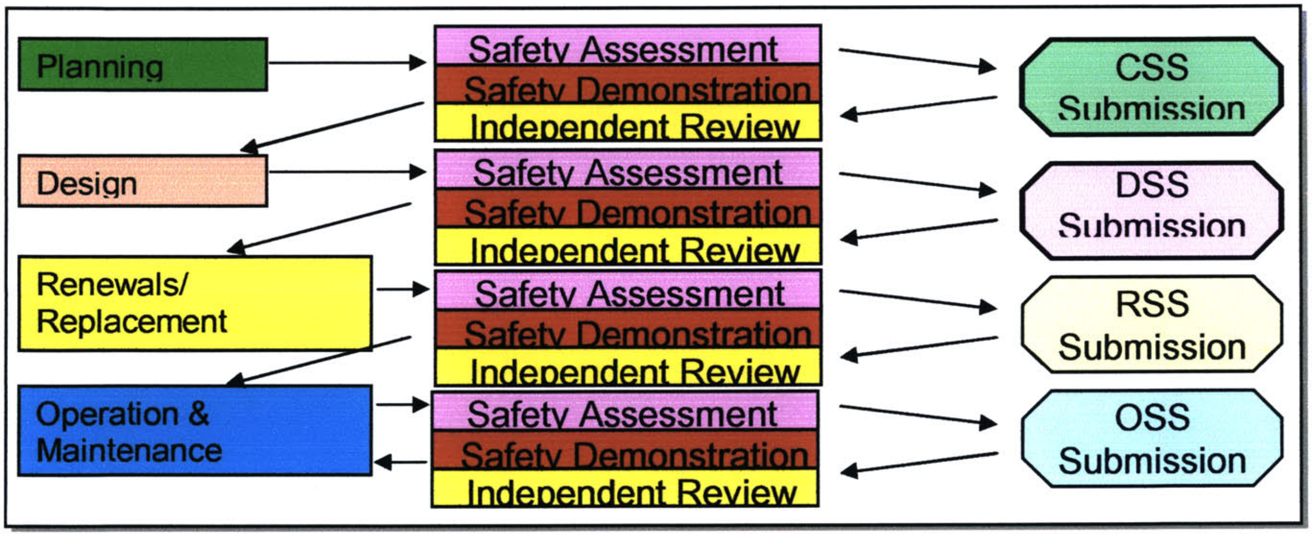


Figure 5-1: Risk Management in Renewals/Replacement of a RTS System[78]

For example at the planning stage, a concept safety submission is formulated which contains a safety assessment and demonstration. This stage would also include a third party review. The next stage is embarked only when the preceding stage has been accepted by all parties. The process repeats for the Design Safety Submission (DSS), RSS (Rehabilitation Safety Submission) and Operation Safety Submission (OSS). This approach assures that risk is managed at every stage of the project and there is ownership and liability for open risks.

---

[78] Adapted from the LTA Project Safety Review (PRS)Process

5.2.3 Strategy Execution

The success of any strategy lies in its execution. With a large scale exercise such as RTS renewals or replacement it would be prudent to formulate an execution strategy as well as back-up plans to ensure that this exercise is well managed and the cutover from the old to refurbished/replaced system seamlessly executed. The old adage that if you fail to plan than plan to fail holds meaning here.

5.2.4 Design Strategies

To the extent of this report, the strategies that have been discussed here delineate between new designs and existing operational systems. It would be beneficial to look at end of life cycle strategies from the design viewpoint upstream of the value chain in particular the architecture of RTS systems. The theme of the architecture based on current worldwide direction would with Architecting For the Environment (Architecting For X =AFX) and at a more strategic level Design For Environment (DFE). The AFE should then address downstream issues such as interfacing, modularization and concepts, such that end of life cycle challenges are more easily accomplished.

Bibliography

Anon., “White Paper launches metro bonanza”, Railway Gazette International, Vol. 152, issue 2, p61, Feb. 1996

Blanchard, B.S. and Fabrycky, W.J., Systems Engineering and Analysis, Prentice Hall, 1998

Bennett, K., Legacy Systems: Coping with Success, IEEE Software, 0740-7459/1994

Bennett, S., Madrid confirms its low-cost approach - Rapid Transit, International Railway Journal, May 2003

Bisbal, J. et al, Legacy Information Systems: Issues and Directions, Trinity College Dublin, 1999

Bollinger, C.R. & Ihlandfeldt, K.R, The Impact of Rapid Rail Transit on Economic Development, Journal of Economics, (42), 1997

Brooke, C. & Ramage, M., Organizational Scenarios and Legacy Systems, International Journal of Information Management, 2001

Christensen, C.M., The Innovator’s Dilemma, Collins Business Essentials, 2005

Christensen, C.M., The Innovator’s Dilemma: When New Technologies Cause Great Firms to Fail, HBS Press, 1997

Chew Tai Chong , See Tow Pak Wei & Leong Kwok Weng, The Singapore Rail Network For 21st Century A Driverless Mass Transit Network, approx.1999.

Chikofsky E.J. and Cross H.H.J, Reverse Engineering and Design Recovery: A Taxonomy, IEEE, January 1990

Chockie A. & Bjorkelo, K., Effective Maintenance Practices to Manage System Aging, Annual Reliability and Maintainability Symposium, 1992

Prof. Ed Crawley, System Architecture Lecture, 15 September 2006

Fielding, G.J., Managing Public Transit Strategically, Jossey-Bass Inc, 1987

Fourace P. & Dunkerley C., Mass Rapid Transit Systems for Cities in the Developing World, Transport Review, 2003, Vol. 23, pp299-310

Flyvbjerg, B., et al, Underestimating costs in public works: errors or lies?, Journal of the American Planning Association, Vol. 68, 2002

Guidice, F. et al, Product Design for the Environment – A Life Cycle Approach, Taylor and Francis, 2006

Gillen, D. and Levinson D., Assessing the Benefits and Costs of ITS – Making the Business Case for ITS Investments, Kluwer Academic Publishers, 2004

Hulme, T.W. & Burchell,A.J., "Tunnelling project in Singapore: an overview", Tunnelling and Underground Space Technology, Vol. 14, No.4, p409-418, 1999, Elsevier Science Ltd.
Hine, J. and Preston, J., Integrated Futures and Transport Choices, Ashgate, 2003

Implications of the Theories of Complexity for the Co-evolution of the Business Process & Information Systems Development, EPRSC Review Report, Grant GR/MO2590/01

Jonson, G. and Tengstrom E., Urban Transport Development – A Complex Issue, Springer, 2006

Kirby, A., Urban Transport and the Environment – An International Perspective, Elsevier, 2004

R.Krishnan, J.P.Copsey, R.G. Algeo & J.N. Shirlaw, Design of the civil works for Singapore's North East Line, Tunnelling and Underground Space Technology, Vol. 14, No.4, p433-448, 1999, Elsevier Science Ltd

Land Transport Authority, Design Criteria Specifications for Contract 759, Singapore, approx. 1997

Leong K.W., Lim H.M., Lin M. & A.S. Kairon, Land Transport Authority Replacement Grant Procedure, 2002

Libov, C., County set to phase in replacement of 12 Metromover cars, Miami Today, 30 March 2006

Nijkamp P, et al, Transportation Planning and the Future, Wiley, 1998

Mintzberg, H. et al, The Strategy Process, Prentice Hall, 1992

Prof. Chris Magee, SDM Lecture on Legacy Systems and Reusability, Fall 2006

Prof. Coughlin, J.F., Transportation Policy and Environmental Lecture, Spring 2006

Rose, C.M., A New Approach to End-of-Life Design Advisor (ELDA), IEEE, 2000

Sage, A.P., Systems Engineering and Systems Management for Reengineering, Journal of Systems Software, 30:3-25, 1995

Maier, M.W. & Rechtin, E., The Art of Systems Architecting, CRC Press, 2002

McGee, J, Legacy Systems: Why History Matters, esj.com, 2005

Mintzberg H. & Quinn, J.B., The Strategy Process, Concepts and Contexts, Prentice Hall, 1992

Muller R., Germany's First Fully Automated Metro Status Report, UITP 78th Metro Assembly, Tehran, May 2004

Profillidis, V.A., *Railway Engineering*, Avebury Technical, 1995

Qiu, L.F., Soil Conditioning for modern EPBM Drives, Tunnels & Tunneling, December 2004

Rechtin, E., Systems Architecting – Creating & Building Complex Systems, 1991
Ross, J., Management Philosophy of the Greater London Authority, Public Money and Management, Oct-Dec 2001

Schneider, J. et al, Asset Management Techniques, 15th PSCC, Liege, 22-26 August 2006
Shaoul, J., A Financial Appraisal of the London Underground Public-Private Partnership, Public Money and Management, Apr-Jun 2002

Solomon, R et al, Electronic Part Life Cycle Concepts and Obsolescence Forecasting, IEEE Vol. 23 Issue 4, 2000

Stephen Adolph, W., Cash Cow in the Tar Pit: Reengineering a Legacy System, IEEE, 1996
Tomlinson J.S, et al, Functional Discovery to Enable Confident Change, INCOSE Conference, 2000

Ulrich, K. and Eppinger, S.D., Product Design and Development, McGraw Hill, 2000

Urban Mass Transport Administration, Ventilation and Environmental Control in Subway, p16-17, TR News, November-December 1987, United States

Brebbia C.A. and Wadhwa, L.C., Urban Transport XI, WIT Press, 2005

Prof. Eric Von Hippel, SDM Lecture on Innovation in the Marketplace, Spring 2006

Vuchic, V.R., Urban Transit: Operations, Planning and Economics, Wiley, 2005

W.K. Bernard Tan, J.C. Chin, C.K. Lee & K.F. Wong, Planning and design of a Civil Defense Shelter in Singapore, Tunneling and Underground Space Technology, Vol. 14, No.4, p509-512, Elsevier Science Ltd, 1999

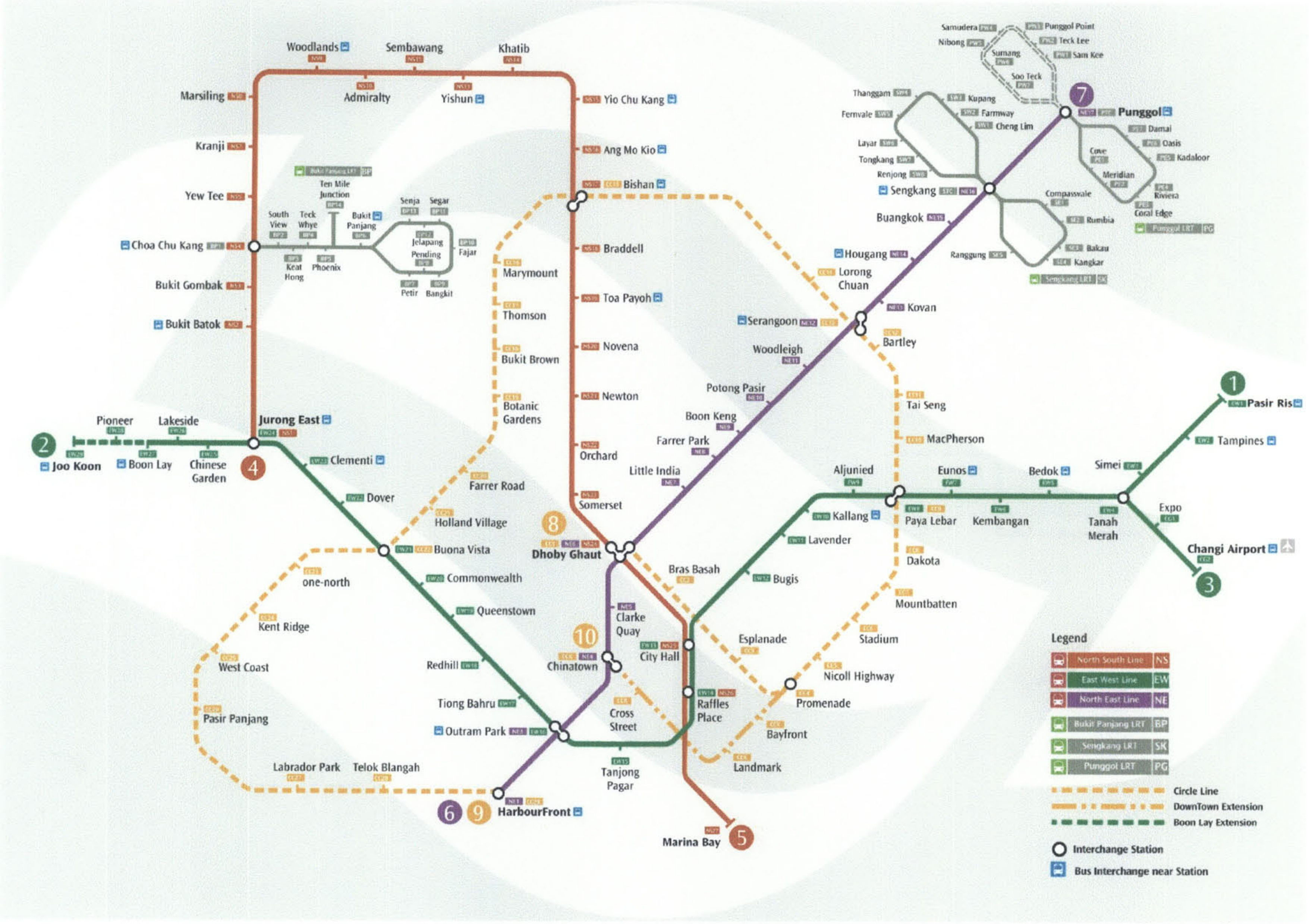
Warren, I, The Renaissance of Legacy Systems, Springer, 1999

Prof. Nigel Wilson, Transit Management Lecture, Fall 2006

J.E. Whitbread, Slab track and non ballasted track, Paper 3.14, Third Track Sector Course (Railway Civil Engineering), Railway Industry Association, London, Lontec Ltd, 1989

Vickerman, R., The Regional Effects of Experience with the Private Finance of Transport Infrastructure, 43rd Congress of European Regional Science Association, August 2003

APPENDIX 1 –Rail Layout Singapore with Lines under Construction



Mass Rapid Transit System Map, © 2006 Land Transport Authority Singapore

APPENDIX 2 – Interviews Conducted with Industry Experts

(A) Interview with Mr. Douglas Heitzenrater, Manager, Fixed Facilities/Wayside, Bombardier

Mr. Heitzenrater noted that for the automated people mover offered by Bombardier, the tunnels and bridges i.e. Civil Infrastructure had a life span of about 50 years. The life span of the Civil Infrastructure hinged on the quality control practiced during the construction of the infrastructure and the maintenance of the infrastructure. If the infrastructure is built on poor quality practices the problems would only show after the system operation. Based on his experience, the one governing factor of the depreciation of a civil infrastructure was the corrosion of re-bars or down to the structure. Mr. Heitzenrater opined that more should be done on implementing proper fixtures to maximize the life cycle of civil infrastructure.

In addition, he noted that current civil infrastructure built is very light while the weight of rolling stock is increasing given the complexity in designs. The running of a heavy vehicle on a light infrastructure would subject the infrastructure to excitation which could result in fatigue of the structure (cyclic loading). Here it was felt that clients should scope their projects correctly and manufacturers should also note the differences in system interfaces to accurately determine the life cycle span and maintenance strategies.

On the power distribution system (PDS), he opined that the management and replacement of the system was more straightforward. Depending on the feed structure i.e. single or dual the maintenance and replacement of a single feed structure would be more complicated given that there was no redundancy. Again the point stressed that proper maintenance would allow for more maximized life of the system.

(B) Interview with Mr. Lewis C. Murascalo, Director, System and Vehicle Engineering and Mr. Jay Kapadia, Manager of System Engineering, Bombardier

Mr. Kapadia noted that at present their clients are requesting for systems that take into account the operation over the entire life cycle. For example in the automated people mover system for London Heathrow Terminal 5, the client has asked for a system context that includes the dismantling and disposing of the system. Mr. Kapadia, noted that while this was a new requirement it does highlight that what happens to a transit system at the end of their life cycle is gaining importance and attention of clients and manufacturer's albeit not at a fast enough rate.

Both Mr. Murascalo and Mr. Kapadia emphasized the point that if the system is maintained well then it will last its entire life span. Both felt that maintenance was being overlooked by transit Operators and as a result the design of the transit system was being penalized.

Mr. Kapadia also noted that standards do play a part in the life cycle of a system. He quoted the example of RoHS[79] where this would definitely impact the extension of life for transit systems. Thus given the long life spans of transit systems the only method to overcome being caught by standards non-compliance would be to over design way above standard requirements such that the system does not become redundant half way through its life. This over design would be translated as costs and thus would not present a viable business case to build a transit system.

Mr. Kapadia opined that one strategy to note for future designs would be Design for the Environment (DFE). Given the existence of the Kyoto Protocol and now the UITP Environment Charter, it would be prudent for manufacturers to ensure that their systems are designed for the Environment. The system being implemented at London Heathrow Terminal 5 where the scope of the project covers the disposal and dismantling of the system elucidates this point further.

On the notion of building redundancy into the system to help cope with end of life cycle of systems i.e. to facilitate system change out, both Mr. Murascalo and Mr. Kapadia felt that this was important and quoted two examples of systems in the US that have undergone end of life cycle change out. A brief account of these projects is given below.

---

[79] EU Legislation, any new electrical and electronic equipment put on market from July 1st, 2006 must meet RoHS standards (Restriction of hazardous substances including Lead, Cadmium, Mercury, and other elements .) Compliance with 6 elements mandatory and 22 other elements recommended. Penalty example: Failure to comply with the requirements of the UK's RoHS Regulations will result in the removal of manufacturers' products from the market place, a term of imprisonment not exceeding three months and/or a fine of up to £5,000.

Tampa International Airport, Florida APM System

On the Tampa International Airport system which has been operational since 1971, the vehicles on this system were replaced in 1995 and 1996. This represented a vehicle life span of about 24 to 25 years well above the vehicle specified life span of 20 years. In 2002, the system was expanded and 4 more vehicles were added.

For the guideway leading to Terminal C half of it was replaced and for Terminal F the power and signal rails were replaced. Given the need of the airport to have the system functional and operational at all times, the replacement of these vehicles and the guideway refurbishment was a challenge.

For this particular case in terms of guideway refurbishment what helped was the dual guideway leading to each terminal. The work was staged such that work occurred on one guideway at any one time and a cutover plan implemented once the work was done to switch over to another guideway. With the detailed staging of the work and the existence of dual guideways, the work went on seamlessly and without a hitch.

Atlanta International Airport System

In the Atlanta International Airport System, with the introduction of the new vehicles on the existing infrastructure in 2001, vehicles were changed out in batches and tested rigorously at the Bombardier test track. As Mr. Kapadia put it, the vehicles were tested to be 'backward compatible' with the existing signaling sub-system, supervisory control system and power distribution system.

(C) Interview with Mr. Jeff Stayer, Consultant, Bombardier

Mr. Stayer opined that the best strategy to manage end of life cycle challenges with transit systems is to leave it to the manufacturer. There is truth to this statement given that the manufacturers know their system best and are more experienced in terms of operations and maintenance of the system. The manufacturers also have an in depth and worldwide knowledge of their systems given that they operate all over the world. The manufacturers are also in a better position to manage the risk and the client need not worry about the management of the risks. In this respect, to ensure seamless and reliable operation, it would be prudent to leave it to the manufacturer. Mr. Stayer noted though that in the US context for, manufacturer's to take over the operations and maintenance on systems already operated by transit authorities would be near impossible. The simple reason being the high barrier to entry posed by unions in the US.

Mr. Stayer added that the quality of maintenance carried out is imperative to ensure maximum life out of a transit system. Mr. Stayer provided the example of Miami Dade Transit which operate and maintain their system. Miami Dade Transit is in the process of replacing 12 cars on their system at a cost of $25.5million which is to be completed by 2008[80]. Mr. Stayer stated that the vehicles are still bellow the 20 year life span but suspects the early retirement due to the quality of maintenance carried out.

(D) Interview with Mr. Mick Franzetta, Vice President, Neihu Project, Bombardier

Mr. Franzetta is currently involved with the Neihu Project which encompasses work on a green field and brown field site. Based on Figure A3-1 the green field site is from Nangang Business Park South to Songshan Airport and the brown field site is from Zhongshan Junior High School to Taipei Zoo. The first stage of the works is to construct the line from Nangang to Songshan and the second stage of the works is to remove and replace all existing electrical and mechanical infrastructure from Zhongshan High School to Taipei Zoo. The scope of works includes the provision of 101 married pair vehicles, wayside equipment for 24 stations, the retrofitting of existing 51 married pair vehicles with CityFlo 650 signaling, new Trackwork and a new communication system.

The above example represents the extension of and old line and the refurbishment of the existing non-civil works on the older line. According to Mr. Franzetta, the greatest challenge posed would be the retrofitting of the existing vehicles with Bombardier signaling given that the signaling equipment would need to interface with the Propulsion Control Electronics (PCE) and the Brake Control Electronics (BCE) on the train. An interface card (reversed engineered) would act as a channel between the new and old electronics. However, given the safety criticality of the systems, models of the propulsion and brake system have been constructed and simulations are being run to ensure the correct interfacing and signals are sent. After simulation the plans are to conduct extensive testing and validation to ensure reliable and safe system function.

---

[80] Libov, C., County set to phase in replacement of 12 Metromover cars, Miami Today, 30 March 2006

Mr. Franzetta felt that to mitigate the risk of running different systems from different suppliers working together the only and definite methodology is to go through simulations and a rigorous set of testing. Given the scope of the works it is inevitable that the brown field site would have to be closed and a bus service used to supplement service levels along that line.

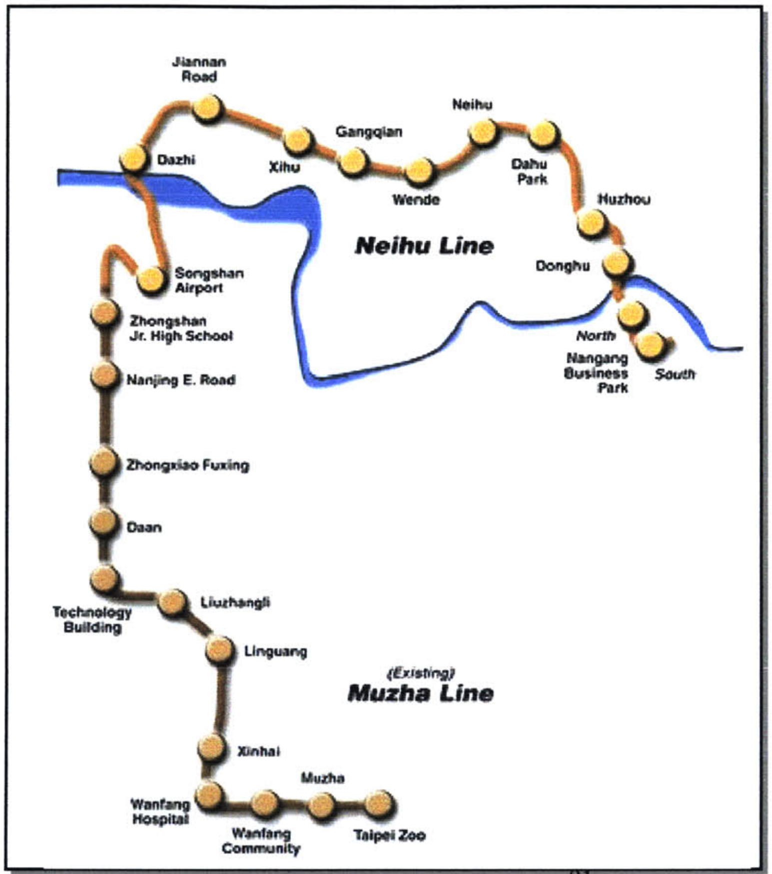


Figure A3-1: Neihu Project, Taiwan[81]

(E) Interview with Mr. John C. Garnham, General Manager, APM, Bombardier

Mr. Garnham provided an example of work that was done with regards to refurbishment of the 450 cars on the BART system, San Francisco in 1995. The work scope encompassed reusing only the carbody, refurbishing the bogies and replacing all other equipment. The key challenge Mr. Garnham noted was the compliance of standards for example, the fire prevention standards by the NFPA-130. The NFPA-130 standard requires a floor fire barrier to withstand a fire for 45 minutes. Given they were reusing the carbody, a design was incorporated of mineral and fire hardened wood on the underside of the floor to meet the NFPA-130 requirement.

---

[81] http://www.bombardier.com/neihu/en/overview.jsp

The question that needs to be posed is why reuse the carbody and why not just purchase new cars. According to Mr. Garnham, by reusing the old cars it cost BART $1 million per vehicle to refurbish them, while purchasing a new car would cost $1.5/2 million dollars. Given the size of the fleet a savings of $225 to $450 million could be reaped.

Another point that Mr. Garnham stressed was that in refurbishing the cars a complete load assessment of the civil infrastructure was carried out by a private consultant prior to the trains running. This was to ensure that all load requirements and safety standards were met.

(F) Interview with James J. Spakauskas, Director, APM Marketing, Bombardier

Mr. Spakauskas shared his experiences working on the vehicle refurbishment for the Orlando Airport . The vehicle refurbishment was carried out at Bombardier's plant in Pittsburgh, and all traction motors and gearboxes were overhauled and reused. The rest of the car was replaced for example, wiring, flooring, roofing, and interior panels. This option worked out cheaper for the Operator as to rehabilitate the cars costs only two thirds the price of a new car. In addition, given the Operator was purchasing three new cars, a schedule of pulling out operational vehicles and swapping them with new vehicles or rehabilitated vehicles was established. This ensures minimal disruption to revenue service. The other point to note is that the time to refurbish the vehicle was an equal duration to build a new vehicle.

(G) Interview with Mr. Mike Mulhern, Executive Director, MBTA Retirement Fund, former General Manager, MBTA

Mr. Mulhern was of the view that it was typical for Operators to maintain their rapid transit systems in a state of good repair. The state of good repair implies that the system works to a reliable standard and is safe to operate. To ensure the state of good repair, maintenance activities are planned around manufacturer's recommendations and also lessons learned by the Operator. This maintenance takes the form of preventive and corrective maintenance. Operators rely on their observations and experience to predict the failure of components and in this respect, tailor their maintenance regimes together with manufacturer's recommendations around this.

While the above is skewed towards the daily/monthly/periodic maintenance of the system it does not address the challenges associated with the system maintenance towards its end of their life cycle. Mr. Mulhern believes that to tackle the challenges of end of life cycle it is paramount to look at the RTS system as a system of systems. Figure's 2-6 and 2-7 further illustrates the point. It is apt to look at an RTS system as such given that each sub-system is unique i.e. based on its functionality, life cycle expectation and maintenance requirements are distinct and different from other sub-systems of the RTS system.

Mr. Mulhern noted that in terms of civil infrastructure this will remain even after its 50-120 year life cycle at least for the case of the MBTA. Assessments can be done to project the life expectation of civil works and the occasional maintenance would include patching of the tunnels and ceilings for leaks.

Mr. Mulhern felt that more attention needs to be paid to technology i.e. electrical and mechanical systems and those manufacturers should ensure that their designs are compliant to international standards and will last over the life span with the proper maintenance of course. Mr. Mulhern stated that given the huge capital costs of rehabilitation or renewals, Operators will try to reuse or extend the life of their transit systems at least for the MBTA case.

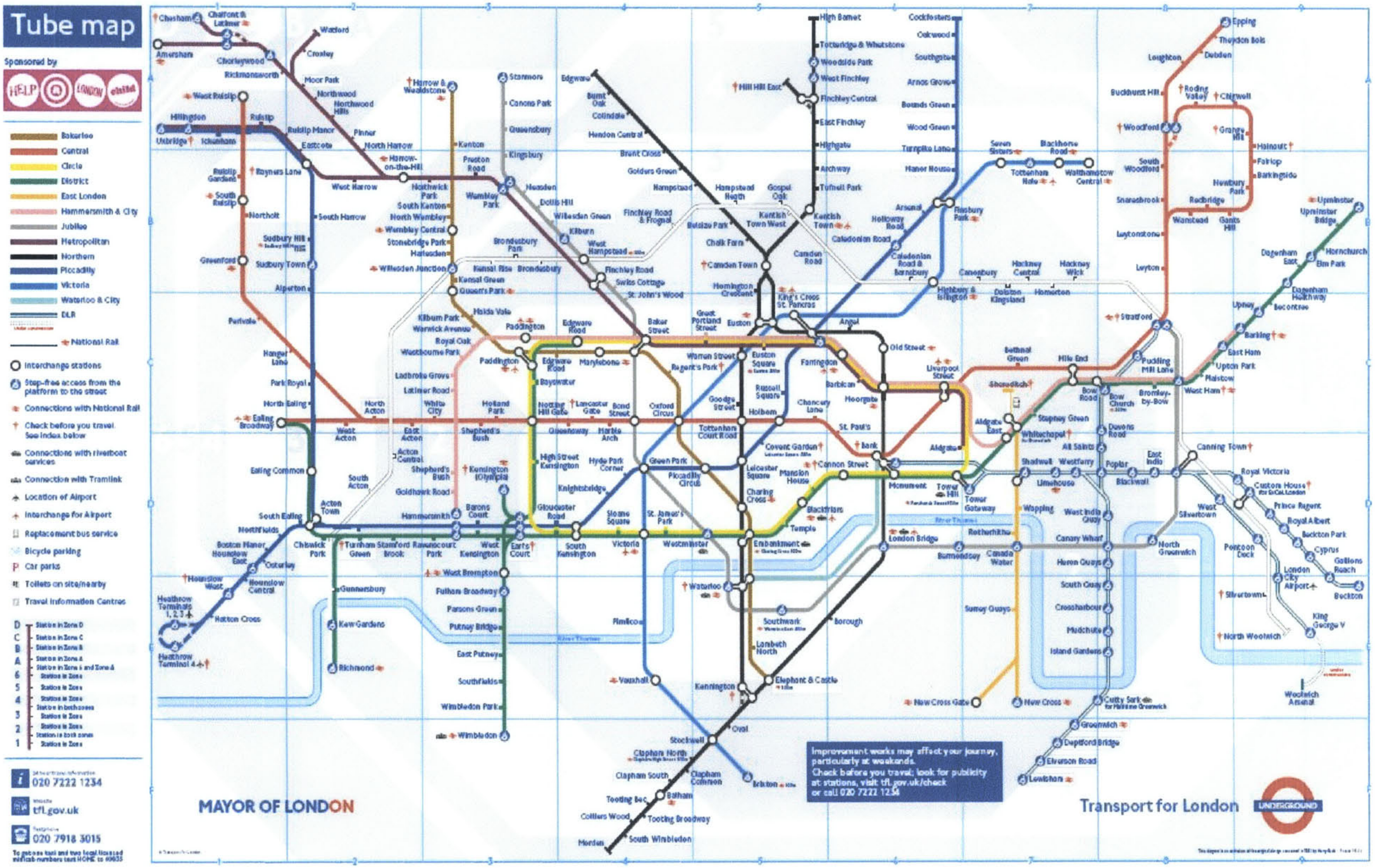
APPENDIX 3 – MBTA System Map[82]

2005 © Robert Schwandl (UrbanRail.Net)

---

[82] http://www.urbanrail.net/am/bost/boston.htm

APPENDIX 4 – London Underground System Map



APPENDIX 5 – London Underground System Lines[83]

London Underground lines

Name	Map colour	First section opened	Name dates from	Type	Length /km	Length /miles	Stations	Journeys per annum (000's)
Bakerloo Line	Brown	1906	1906	Deep level	23.2	14.5	25	95,947
Central Line	Red	1900	1900	Deep level	74	46	49	183,582
Circle Line	Yellow	1884	1949	Sub-surface	22.5	14	27	68,485
District Line	Green	1868	1868-1905	Sub-surface	64	40	60	172,879
East London Line	Orange	1869	1980s	Sub-surface	7.4	4.6	8	10,429
Hammersmith & City Line	Pink	1863	1988	Sub-surface	26.5	16.5	28	45,845
Jubilee Line	Silver	1879	1979	Deep level	36.2	22.5	27	127,584
Metropolitan Line	Magenta	1863	1863	Sub-surface	66.7	41.5	34	53,697
Northern Line	Black	1890	1937	Deep level	58	36	50	206,734
Piccadilly Line	Dark Blue	1906	1906	Deep level	71	44.3	52	176,177
Victoria Line	Light Blue	1968	1968	Deep level	21	13.25	16	161,319
Waterloo & City Line	Teal	1898	1898	Deep level	2.5	1.5	2	9,616

---

[83] http://en.wikipedia.org/wiki/London_Underground

APPENDIX 6 – MBTA Statement of Revenue and Expenses FY1991 – FY 2007[84]

REVENUE	FY1991	FY1992	FY1993	FY1994	FY1995	FY1996	FY1997	FY1998	FY1999	FY2000	FY2001	FY2002	FY2003	FY2004	FY2005	FY2006	FY2007
Operating Revenues																	
Rapid transit revenue	98,322,413	93,911,987	99,176,186	106,743,817	103,679,267	97,830,213	100,033,769	103,466,441	102,248,635	107,788,759	122,304,902	121,522,567	117,016,379	124,192,546	136,256,396	147,500,000	165,937,500
Commuter rail transit revenue	32,997,071	36,363,398	39,827,707	42,602,734	45,079,659	42,707,370	47,653,409	58,005,408	65,378,414	67,535,442	85,223,784	85,144,093	84,853,863	89,083,486	98,790,037	106,500,000	119,812,500
Surface transit revenue	23,361,554	34,418,432	34,660,104	33,031,411	38,825,042	48,452,635	47,064,891	49,753,560	51,949,067	52,791,159	69,950,773	72,115,128	69,081,005	78,102,548	80,080,979	75,000,000	84,375,000
School, senior and paratransit revenue	1,743,999	2,360,839	2,306,948	2,543,547	2,529,952	2,824,403	2,983,030	3,099,076	2,858,044	2,859,236	3,503,448	4,505,779	3,254,543	4,117,525	4,143,754	5,000,000	5,625,000
Advertising and concession revenue	3,584,797	2,760,380	3,248,582	7,036,811	5,813,074	6,954,795	8,334,637	5,421,114	6,887,406	9,406,861	15,536,844	15,095,457	17,116,931	19,557,630	21,610,945	9,649,064	15,083,500
Revenue from real estate operations	8,413,404	8,030,627	7,352,182	7,395,430	9,721,873	12,223,721	13,104,828	19,578,039	17,805,311	18,944,959	22,185,007	22,735,730	26,244,143	29,882,524	26,140,563	30,424,322	33,895,475
Total Operating Revenues:	**168,423,238**	**177,845,663**	**186,571,709**	**199,353,750**	**205,648,867**	**210,993,137**	**219,174,564**	**239,323,638**	**247,126,877**	**259,326,416**	**318,704,758**	**321,118,754**	**317,566,864**	**344,936,259**	**367,022,674**	**374,073,386**	**424,728,975**
Non-Operating Expenses																	
Interest Income	5,359,203	3,666,092	3,695,309	2,503,273	3,420,427	5,248,348	5,914,913	6,303,305	4,032,175	5,346,197	10,686,563	5,563,211	2,587,324	2,062,669	4,361,467	3,579,345	2,937,709
Non-Operating Income	0	1,184,163	988,178	3,225,579	2,779,843	14,008,906	3,167,844	17,389,124	25,270,242	9,154,919	8,331,503	5,368,605	6,962,483	8,673,034	4,194,911	25,227,861	33,364,334
Funds from Federal Government	18,110,310	18,141,994	17,643,018	17,229,943	15,216,023	12,804,006	6,316,525	2,927,123	6,500,000	6,453,228	6,500,000	2,224,876	1,140,131	305,100	6,614,493	10,884,751	8,000,000
Utility Reimbursements	0	0	0	0	0	0	0	89,277	3,246,011	5,110,331	2,221,903	1,850,821	1,996,312	1,772,399	1,534,660	1,724,201	1,583,729
Total Non-Operating Revenues:	**23,469,513**	**22,992,249**	**22,326,505**	**22,958,795**	**21,416,293**	**32,061,260**	**15,399,282**	**26,708,829**	**39,048,428**	**26,064,675**	**27,739,969**	**15,007,513**	**12,686,250**	**12,813,202**	**16,705,531**	**41,416,158**	**45,885,772**
Revenue from Dedicated Sources																	
Funds from Local Governments	115,748,275	118,641,982	121,608,032	124,648,231	127,764,437	130,958,548	134,232,512	137,588,326	141,028,033	144,553,734	144,553,734	142,872,642	141,142,768	139,437,832	137,732,280	136,026,868	139,427,540
Revenue Receipts from State Sources	413,823,846	454,656,148	462,895,241	481,213,484	429,672,522	433,451,501	483,134,528	515,870,434	577,629,697	587,504,666	590,772,447	664,350,000	682,094,554	686,976,316	704,620,528	712,585,739	733,963,311
Total Dedicated Revenues:	**529,572,121**	**573,298,130**	**584,503,273**	**605,861,715**	**557,436,959**	**564,410,049**	**617,367,040**	**653,458,760**	**718,657,730**	**732,058,400**	**735,326,181**	**807,222,642**	**823,237,322**	**826,414,148**	**842,352,808**	**848,612,607**	**873,390,851**
Total Revenues:	**721,464,872**	**774,136,042**	**793,401,487**	**828,174,260**	**784,502,119**	**807,464,446**	**851,940,886**	**919,491,227**	**1,004,833,035**	**1,017,449,491**	**1,081,770,908**	**1,143,348,909**	**1,153,490,436**	**1,184,163,609**	**1,226,081,013**	**1,264,102,151**	**1,344,005,598**
EXPENSES																	
Operating Expenses																	
Wages	246,348,057	248,014,590	243,920,249	265,971,128	238,107,551	240,328,601	242,549,744	247,641,361	281,339,617	283,120,856	291,092,991	307,843,432	311,714,068	319,328,460	337,189,978	343,313,907	354,756,887
Fringe Benefits	74,868,914	84,328,754	94,391,807	102,058,363	87,032,361	78,965,914	83,027,817	91,083,910	91,729,346	96,735,355	99,401,191	97,520,302	103,997,754	114,468,705	125,336,543	147,179,939	160,969,998
Payroll Taxes	21,924,116	22,057,309	22,228,354	23,901,613	19,802,579	19,097,646	19,609,759	19,455,266	21,714,920	23,233,260	22,387,234	23,190,933	23,552,709	24,406,912	26,900,012	27,319,289	28,275,514
Materials, Supplies and Services	88,474,782	88,426,300	94,862,114	89,332,780	76,177,202	73,848,592	78,657,736	82,135,375	100,055,308	101,024,633	110,677,687	111,318,591	118,917,517	108,786,619	121,716,973	137,786,432	145,371,819
Casualty & Liability	11,999,269	12,748,991	12,000,000	12,000,000	13,191,440	10,739,030	11,115,020	11,434,824	10,496,940	10,212,363	10,239,156	13,361,808	13,281,755	15,411,442	14,672,240	14,713,614	15,713,614
Purchased Commuter Rail Expenses	92,814,866	96,782,546	106,628,421	108,377,012	106,268,070	105,044,469	111,816,757	139,469,905	160,856,086	167,978,611	172,540,450	185,824,276	192,605,170	213,691,188	216,403,861	215,619,026	223,729,831
Purchased Local Service Charges	14,027,639	14,442,698	15,520,538	15,985,342	17,146,104	18,113,604	22,149,924	23,812,753	24,766,569	25,251,475	28,996,629	32,131,530	35,172,502	38,327,589	43,985,446	50,107,891	54,771,505
Financial Service Charges	2,740,697	3,978,965	3,539,713	3,525,554	3,435,558	3,213,997	3,279,199	3,355,630	3,117,467	3,064,715	1,504,828	1,544,492	1,546,016	1,834,522	1,801,021	1,728,960	1,728,960
Total Operating Expenses:	**553,198,340**	**570,780,153**	**593,091,196**	**621,151,792**	**561,160,865**	**549,351,853**	**572,205,956**	**618,389,024**	**694,076,253**	**710,621,268**	**736,840,166**	**772,735,364**	**800,787,491**	**836,255,437**	**888,006,074**	**937,769,058**	**985,318,128**
Debt Service Expenses																	
Interest	124,761,514	137,300,940	131,342,466	129,185,075	139,986,352	164,632,160	174,661,166	187,795,839	194,598,408	187,027,313	164,976,429	193,845,930	216,966,041	204,783,748	223,291,802	207,697,820	235,309,978
Principal Payments	43,505,017	66,054,949	68,967,825	55,133,561	60,802,667	79,424,477	88,563,667	97,927,056	101,471,536	104,534,949	111,645,667	131,959,750	110,349,327	117,798,529	95,651,923	111,407,268	110,297,178
Lease Payments	0	0	0	22,703,833	22,552,234	14,055,957	16,510,095	15,379,309	14,686,838	15,265,959	14,918,033	15,261,176	15,908,155	16,423,708	17,577,942	17,695,108	17,814,686
Total Debt Service Expenses:	**168,266,531**	**203,355,889**	**200,310,291**	**207,022,469**	**223,341,253**	**258,112,594**	**279,734,928**	**301,102,204**	**310,756,782**	**306,828,221**	**291,540,129**	**341,066,856**	**343,223,523**	**339,005,985**	**336,521,667**	**336,800,196**	**363,421,842**
Total Expenses:	**721,464,871**	**774,136,042**	**793,401,487**	**828,174,261**	**784,502,118**	**807,464,447**	**851,940,884**	**919,491,228**	**1,004,833,035**	**1,017,449,489**	**1,028,380,295**	**1,113,802,220**	**1,144,011,014**	**1,175,261,422**	**1,224,527,741**	**1,274,569,254**	**1,348,739,970**
Surplus	**1**	**0**	**0**	(1)	**1**	(1)	**2**	(1)	**0**	**2**	**53,390,613**	**29,546,689**	**9,479,422**	**8,902,187**	**1,553,272**	(10,467,103)	**(4,734,372)**
Deficiency Fund	0	0	0	0	0	0	0	0	0	0	(13,130,183)	(1,075,047)	(5,363,232)	(4,770,114)	(1,553,270)	10,467,104	4,734,373
Capital Maintenance Fund	0	0	0	0	0	0	0	0	0	0	(36,583,800)	(24,116,436)					
Net Surplus/(Deficit)	1	0	0	-1	1	-1	2	-1	0	2	3,676,630	4,355,206	4,116,190	4,132,073	2	1	1

---

[84] Source ESD227J Transit Management Assignment 2