

The Support Organization: A Strategic and Value Adding Force

- A Study of Maintenance of Rail Transit Vehicles

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November 2006

Preface

This master's thesis aims to provide a holistic approach to maintenance management. The maintenance organization has such great influence on the company's ability to achieve its corporate mission, and must therefore have a central strategic role in the company. The ambition is to relate the most widely used maintenance theories to the mission statement, the market, and the value drivers of the organization. The theories are not explained in full detail, so the readers are encouraged to further explore areas that are of particular interest.

A large part of the study was carried out during the hot Swedish summer of 2006 at Systecon's office in downtown Malmö. I want to thank all the colleagues at Systecon for their support and pleasant company, and special thanks to Pär Sandin for initiating this interesting master's project and for taking on the role as my company supervisor.

Finally, my greatest thanks to my supervisor and mentor Professor Hans Ahlmann who has always been available for feedback and challenging discussions, even during the finest summer days at his summer residence at Sladö in the Västervik archipelago. Hans has been a pioneer in market and profit driven maintenance management, and he is the founder of the widely spread Life Cycle Profit (LCP) concept. Hans' vast knowledge within the field of maintenance management and his large repertory of funny stories from a long and prominent career has made it a true joy to write this thesis.

I hope you will enjoy reading this thesis as much as I enjoyed researching and writing it, and that it will raise many new thoughts on maintenance management.

Håkan Borgström

November 2006

Abstract

Title: The Support Organization: A Strategic and Value Adding Force - A Study of Maintenance of Rail Transit Vehicles

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Background: Systecon is a leading European consultancy and software company within system logistics, system reliability, maintenance and Life Cycle Cost (LCC) analysis. Historically the military and military suppliers have accounted for the majority of the commissions, but over time other industries have realized that effective maintenance and logistic support can greatly enhance the overall effectiveness of a system and at the same time lower the costs. Hence, more and more companies outside the military are requesting Systecon's expertise and software tools. One of the industries that consult Systecon on support issues is the railway sector. Although the basic support theories are general, every industry has special prerequisites and requirements. Systecon initiated this master's project to analyze and identify improvements to the company's current practices for developing support strategies for public transport companies.

Purpose: The purpose of this master's thesis is to thoroughly analyze the support situation for rail transit vehicles. This includes a description of a typical public transport case and Systecon's engagement. The analyses should result in the development of a structured approach that improves and extends Systecon's current practice. The thesis also describes how Systecon's software should be integrated with the suggested approach.

Methodology: The study is based on a typical public transport case. The case is developed from public transport cases that Systecon is engaged in, but it is not referring to a specific real-life case. Simulation studies are performed in order to gain understanding of complex interrelationships and to study the consequence of various proposed solutions. The result is presented in a framework that systematically describes the concepts required to achieve a

The Support Organization: A Strategic and Value Adding Force

strategic and value driven support organization. The framework embraces concepts from many different theories, where each theory contributes with a different perspective. The ambition is to create a general framework, since it should apply to any type of public transport system.

Conclusions: The public transport case described in this thesis shows that the maintenance function has a large impact on the public transport company's profitability and ability to achieve its corporate mission. This means that the maintenance function has a crucial strategic role in the organization, which calls for a market and value driven management. Hence the traditional cost focused approach based on traditional LCC and logistic support concepts is not sufficient when designing the support organization for a public transport system. This approach must be extended to embrace the support organization's full potential as a strategic and value adding force. This thesis presents a framework for developing a strategic and value driven support organization. The framework relies on established maintenance management theories such as Life Cycle Profit (LCP) and Value Driven Maintenance (VDM). In addition to this the framework also takes inspiration from production management theories, which provides a strong strategic focus. Systecon's software suite has proven to have most of the necessary functionalities required to facilitate the development of a strategic and value driven support organization. However, what must be improved is the integrated use of the tools.

Keywords: LCC, LCP, life cycle cost, life cycle profit, maintenance management, maintenance strategy, public transport, railway maintenance, value driven maintenance, VDM.

Abbreviations

ADL	: Administrative Delay Time
ATC	: Automatic Train Control
BSC	: Balanced Scorecard
CBM	: Condition Based Maintenance
CBS	: Cost Breakdown Structure
CM	: Corrective Maintenance
CMMS	: Computerized Maintenance Management System
CSI	: Customer Satisfaction Index
EBSOM	: European Benchmark Study On Maintenance
FBS	: Function Breakdown Structure
FMECA	: Failure Mode Effectiveness and Criticality Analysis
ILS	: Integrated Logistic Support
KPI	: Key Performance Indicator
KPP	: Key Performance Parameter
LBS	: Location Breakdown Structure
LAC	: Life Acquisition Cost
LCC	: Life Cycle Cost
LCL	: Life Cycle Loss
LCP	: Life Cycle Profit
LCR	: Life Cycle Revenue
LDC	: Life Disposal Cost
LOC	: Life Operational Cost
LORA	: Level Of Repair Analysis
LSC	: Life Support Cost
MDT	: Mean Downtime
MDBF	: Mean Distance Between Failure
MDTF	: Mean Distance To Failure
MLDT	: Mean Logistics Down Time

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MTBF	: Mean Time Between Failure
MTBM	: Mean Time Between Maintenance
MTTF	: Mean Time To Failure
MTTR	: Mean Time To Repair
MWT	: Mean Waiting Time
OMAX	: Objectives Matrix
PDSA	: Plan Do Study Act
PM	: Preventive Maintenance
RAM	: Reliability, Availability, Maintainability
RBS	: Revenue Breakdown Structure
RCM	: Reliability Centered Maintenance
SHE	: Safety, Health and Environment
TPM	: Total Productive Maintenance
VDM	: Value Driven Maintenance

Contents

1	Introduction	13
	1.1 Background.....	13
	1.2 Purpose	13
	1.3 Delimitations	14
2	About Systecon.....	15
	2.1 The Company	15
	2.2 The ILS Toolbox	15
	2.2.1 Opus10.....	15
	2.2.2 Simlox.....	15
	2.2.3 Catloc.....	16
	2.2.4 Madcat	16
3	Methodology.....	17
	3.1 Research Classification.....	17
	3.1.1 Explorative Research	17
	3.1.2 Explanatory Research	17
	3.1.3 Normative Research.....	17
	3.2 Research Methodology	17
	3.2.1 Qualitative Method	17
	3.2.2 Quantitative Method	17
	3.2.3 Preparatory Study	17
	3.2.4 Survey Study.....	18
	3.2.5 Case Study	18
	3.2.6 Experimental Study.....	18
	3.3 Research Quality.....	18
	3.3.1 Reliability	18
	3.3.2 Validity	19
	3.4 Proposed Methodology.....	19
	3.4.1 Literature Review	19
	3.4.2 Interview	19
	3.4.3 Data Collection	19
	3.4.4 Case Description.....	20
	3.4.5 Simulation Study	20
	3.4.6 Framework Design.....	20
4	Theory.....	21
	4.1 The Life Cycle Concept.....	21
	4.1.1 Life Cycle Cost	21
	4.1.2 Life Cycle Profit	22
	4.1.3 Cost/Revenue Breakdown Structure	23
	4.1.4 When to Use LCC and LCP?	24
	4.2 Value Driven Maintenance	25
	4.3 Maintenance Context	26
	4.3.1 Availability	27
	4.3.2 Reliability	28

The Support Organization: A Strategic and Value Adding Force

4.3.3	Maintainability.....	28
4.3.4	Supportability	28
4.3.5	Corrective Maintenance.....	28
4.3.6	Preventive Maintenance.....	29
4.3.7	Balanced Maintenance	29
4.3.8	Integrated Logistic Support	29
5	The Public Transport Case and Systecon's Engagement.....	31
5.1	Background.....	31
5.2	The Scope of Systecon's Engagement	31
5.3	Review of Maintenance Related Agreements.....	32
5.4	Preparation of Maintenance Data	33
5.5	Definition of Maintenance Concept.....	36
5.6	Development and Implementation of Maintenance Plan.....	37
5.7	RAM Verification.....	38
6	Linking Strategic and Value Driven Theories to the Public Transport Case	39
6.1	Public Transport Maintenance from a Manufacturing Strategy Perspective	39
6.2	Life Cycle Cost/Revenue Elements in the Public Transport System.....	41
6.3	The Commuter Vehicles' Life Cycle Phases	42
7	Framework for Developing a Strategic and Value Driven Support Organization	43
7.1	Mission Statement	46
7.2	Understand the Market Place.....	46
7.3	Identify Value Drivers	47
7.4	Define Maintenance Strategy.....	49
7.5	Increased Reliability through Robustness.....	50
7.6	Adaptable Solutions.....	51
7.7	Risk Analysis.....	52
7.8	Trade-off Analysis	53
7.9	Focused Maintenance	54
7.10	Maintenance Outsourcing.....	56
7.11	Optimize Resources to Maximize Profit.....	59
7.12	Strategic and Profit Driven Incentive Program.....	61
7.13	Continuous Improvements.....	64
8	Implementing Strategic and Value Driven Concepts in the ILS Toolbox	65
8.1	Systematic Integration of the ILS Tools	65
8.2	Bal: Preventive Maintenance Analysis and Packaging.....	67
8.3	Opus10: Calculate Optimal Stock Levels and Corrective Maintenance Cost.....	68
8.4	Simlox: Simulate Operational Availability and Resource Utilization	70
8.5	Catloc: Compile the LCP Model and Identify Value Drives	71
8.6	Madcat: Follow-up Analysis and Verification.....	75
8.7	Summary of Suggested Improvements	76
9	Findings and Recommendations	77
9.1	Findings	77
9.2	Recommendations	78
9.3	For Future Research.....	79
	References.....	81
	Appendix I – SINTEF Cost Breakdown Structure	I

The Support Organization: A Strategic and Value Adding Force

Appendix II – The 10 KPIs Used in the VDM Control Panel	III
Appendix III – Simulation with Simlox	V
Appendix IV – Simulation with Simul8.....	IX

1 Introduction

1.1 Background

Systecon is a leading European consultancy and software company within system logistics, system reliability, maintenance and Life Cycle Cost (LCC) analysis.

The software development at Systecon started about 30 years ago with a spares optimization tool. Today the company offers a complete suite of software tools including:

- Spares optimization (Opus10)
- Simulation (Simlox)
- LCC analysis (Catloc)
- Maintenance data categorization and analysis (Madcat)

Historically the military and military suppliers have accounted for the majority of the commissions, but over time other industries have realized that effective maintenance and logistic support can greatly enhance the overall effectiveness of a system and at the same time lower the costs. Hence, more and more companies outside the military are requesting Systecon's expertise and software tools.

One of the industries that consult Systecon on support issues is the railway sector. Although the basic support theories are general, every industry has special prerequisites and requirements. Systecon initiated this master's project to:

- analyze the support situation for rail transit vehicles
- present a solution for how the development of a maintenance organization should be performed
- evaluate and describe how Systecon's software suite should be integrated as a decision support tool in this process, and identify necessary improvements to the software

1.2 Purpose

The objective is to thoroughly analyze the support situation for rail transit vehicles. This includes a description of a typical public transport case and Systecon's engagement. The analysis will rely on a combination of conventional maintenance theories and production management theories. Production management thinking implies a different perspective to the project, which hopefully will extend and challenge the traditional approach.

The result is presented as a framework of concepts that facilitate a successful development of a strategic and profit driven support solution for public transport systems. These concepts should identify areas where Systecon can improve and extend the current practice.

The thesis also describes how the concepts presented in the framework should be integrated with Systecon's ILS toolbox. This includes a detailed evaluation of Systecon's simulation tool Simlox. An evaluation of Systecon's other software tools is also part of the study, but the focus is on Simlox, since it is a relatively new and very flexible tool that has a large potential for

improvements. Simlox is also the software that is most frequently used by Systecon in the train maintenance case.

1.3 Delimitations

The thesis is limited to the support analysis that follows after the design process is completed. Hence, all maintenance data specified by the manufacturer is considered as fixed input to the analysis. From a Life Cycle Profit (LCP) point of view the design process is the phase in a system's life cycle where improvements will have the largest impact on the total cost of the system over its lifetime (e.g. robust design, design for maintainability etc.). The reason this important process is disregarded in this project is that this phase has typically already been completed in the type of case that the thesis is intended to analyze.

The evaluation of Systecon's software tools is limited to the functionality of the tools (i.e. what they can achieve), and other aspects will not be considered.

2 About Systecon

2.1 The Company

Systecon is an independent, employee-owned consultant firm that offers services in Integrated Logistic Support (ILS). The company helps clients to increase reliability, achieve more efficient resource utilization, and take control of the support costs of large complex systems.

For almost four decades, Systecon has been working with ILS projects within both the military and the civil sector. Among the clients are: Boeing, Bombardier, British Aerospace, Ericsson, FMV, Lockheed-Martin, SAAB, SAS, SL, SPP, Statoil, Tetra Pak, Vattenfall and Volvo Cars.

Besides Sweden (Stockholm, Gothenburg, Malmö), Systecon is also present in the UK market through the partly owned subsidiary, Systecon UK. The international network also includes partners in, among other countries, Norway, Germany, Italy, Greece, Turkey, USA, Australia, Singapore, China, South Korea, Taiwan and South Africa.

2.2 The ILS Toolbox

2.2.1 Opus10

The first version of Opus was released in the 1970s, and today's version is the result of 30 years of continuous development. The software offers state-of-the-art optimization methods that solve complex support scenarios. With Opus10 it is possible to perform spare part optimization on scenarios with unlimited sites and systems including both repairable and discardable items. Some of the main features in Opus10 are:

- Full system breakdown capability without indenture level constraints
- Full commonality capability for systems and items
- Full logistics support modeling capability without echelon constraints
- LSC optimization of repairable, partly repairable and discardable items
- LORA – Location of Repair (and Resources) Analysis

Results from Opus10 are presented as the optimal KPI value per invested capital. This is illustrated in a cost/effectiveness diagram where the effectiveness KPI is plotted against the Life Support Cost (LSC).

2.2.2 Simlox

Opus10 is limited to analyze spares optimization problems. Simlox is a simulation tool that complements Opus10 with detailed analysis of other resources in the support organization, for example, personnel and tools. The software is using a stochastic simulation approach (based on Monte Carlo technique). Simlox offers:

- Possibility to include operational profiles in the model
- Extended flexibility in the analysis of resources

- Time dependent results

With these features Simlox can be used to extend and verify the Opus10 model. Results from Simlox are typically presented in graphs showing the state of a system or a resource over time. Other valuable information obtained from Simlox is graphs showing the reasons for unavailability over time. These results should give a good indication of how the system will perform in a real-life situation.

2.2.3 Catloc

Most computer LCC models today are created in some spreadsheet software. A spreadsheet software could with success be used to calculate the total LCC and perform some basic analysis of the cost distribution. However more complex scenarios could be difficult to model, analyze and maintain with this type of software. Catloc is a specialized LCC tool that allows for detailed cost distribution analysis of LCC models. In Catloc, cost atoms are linked to a set of domains (material, station, task, resource, and time). The general idea is that once the model is created it is possible to obtain detailed information on, for example, the cost of material distributed over time, or the cost of resources per station etc. Catloc is designed to:

- Handle any type of LCC model
- Produce different cost breakdowns
- Perform sensitivity analysis

In addition to finding the total LCC, Catloc is also used to identify cost drivers and perform sensitivity analyses in order to analyze what-if scenarios, and thus understand how robust the system is.

2.2.4 Madcat

Madcat (Maintenance Data Categorization and Analysis Tool) is a software tool designed for the analysis of reliability development over time. The software uses system structures and defined cost elements to categorize and analyze experience data regarding flow of cost and events, cost profiles, trends and prognoses. Madcat can also be used for warranty evaluation, component life-length analysis and optimization of maintenance intervals. Key features in Madcat are:

- Multi-dimensional categorization
- Trend analysis
- Reliability data estimation
- Consequence analysis
- Maintenance optimization support
- Verification functions

3 Methodology

3.1 Research Classification

3.1.1 Explorative Research

The purpose of an explorative research is to obtain fundamental knowledge and understanding of the field study. This method is valuable in the early stages of the research process when the insight in the problem is vague. The explorative research aims to form a clear picture of the problem and how the succeeding analysis should be carried out⁽²⁰⁾.

3.1.2 Explanatory Research

The explanatory research intends to clarify cause-effect interrelationships. This method focuses on variables that are central to the analysis. The interrelationships could be simple or complex, and are usually explained through logic reasoning based on established theories and declarative knowledge⁽²⁰⁾.

3.1.3 Normative Research

The target of normative research is to predict how proposed concepts and changes will influence the system and the organization. The central cause-effect interrelationships identified in the explanatory research are fundamental input to this analysis⁽²⁰⁾.

3.2 Research Methodology

3.2.1 Qualitative Method

Qualitative investigations concern the gathering and analysis of data that cannot be quantified in a meaningful way (i.e. numerically). These studies are usually not structured beforehand, and therefore call for an explorative approach⁽²⁰⁾.

3.2.2 Quantitative Method

Quantitative studies regard the gathering and analysis of data that can be expressed numerically. In a quantitative study there are many possible arrangements for how the investigation is carried out and how the data is being expressed⁽²⁰⁾.

3.2.3 Preparatory Study

Most research projects begin with a preparatory study, which aims to develop a deeper understanding of the problem. This includes reviewing literature and analyzing available data and previous research projects within the same field. The preparatory study is a great way of learning more about the research field and it often generates many ideas for the proceeding

analysis. An elaborate problem description could provide much of the information that is necessary for the analysis, and thus reduce the need for additional data gathering⁽²⁰⁾.

3.2.4 Survey Study

The survey study is used to obtain information about a larger population. The survey is given to a sample population that is selected to represent the population the study is targeting. The conclusions that can be drawn from a survey study depend on the size of the sample population, how the sample population was selected, and the response rate. The survey usually compares things against each other, and the results are of statistical nature and are presented in tables and graphs⁽²⁰⁾.

3.2.5 Case Study

A case study is a thorough and detailed analysis of one specific case. The focus allows the analyzer to gain deeper insight in areas that are of specific interest. The approach also makes it possible to discover conditions that were not known beforehand. The selection of a case is based on some predefined criteria, which could be, for example, a typical case or an extreme case⁽²⁰⁾.

3.2.6 Experimental Study

The experimental study gives information about the behavior of a process or customer group etc. The experiment is carried out either as a field study or in a laboratory. The technique provides experimental data that can be used for further analysis. A special type of experimental study is simulation, where the experiment is performed on a computer model of the real-life scenario. In a simulation study, the modeling process requires a thorough understanding of the situation that is being analyzed⁽²⁰⁾.

3.3 Research Quality

3.3.1 Reliability

Reliability regards the accuracy of the information that is used in the research study. This concerns all the methods and measuring tools that are used for collecting the data, as well as how the data is handled by the researcher. Every research study should strive for the highest possible reliability. When gathering subjective information through questionnaires or interviews, the outcome is highly dependent on how the questions are formulated. The quality of objective quantifiable data mainly depends on the reliability of the measuring process. Statistical methods must be used when it is too expensive and time consuming to collect data about every single entity of a large selection. In this case the choice of statistical method is important for the reliability of the study⁽¹⁵⁾.

3.3.2 Validity

Validity regards whether the information that is used in the research study actually measures what it is intended to measure. This means that even if the information is accurate it may still be useless if it does not measure the right things. Hence high reliability and high validity must both be satisfied in order to guarantee high research quality. To achieve high validity it is important to carefully investigate and clearly specify, in the problem formulation, the type of information required for the research and how it should be obtained⁽¹⁵⁾.

3.4 Proposed Methodology

3.4.1 Literature Review

Established life cycle cost, logistic support, and production management theories will constitute the foundation for the framework design. The initial phase of this thesis is dedicated to a *desk study* review of the current literature within the above mentioned fields, as well as related master's thesis and disputations. The aim is to understand how the different fields are interrelated and to distinguish the theories that best apply to the train maintenance scenario.

Throughout the project it may be necessary to conduct further literature reviews to follow-up on topics identified in the interviews, or other issues that arise.

3.4.2 Interview

Qualitative data is collected from interviews and meetings with involved parties. A first round of interviews will be conducted during the early stages of the project to gain a deeper knowledge of the specific requirements for train maintenance. This involves internal interviews with consultants at Systecon, as well as attending external meetings with maintenance suppliers and traffic owners.

A second round of internal interviews is planned later in the project during the analysis of Systecon's current approach to the train maintenance problem. The interviews will be conducted as open discussions rather than following a strict set of questions.

3.4.3 Data Collection

Quantitative data is collected from various sources. All maintenance related data such as failure rates and preventive maintenance (PM) intervals is provided by the train manufacturer. Primary cost data such as cost of spares and man-hour cost is collected from the companies that are associated with the specific costs (e.g. the maintenance supplier, the manufacturer, and the traffic owner). Estimates based on expert opinion and secondary data is used if primary data is not available. All data gathered for the study will be used to describe a typical real-life case, but it will not refer to a specific real-life case.

3.4.4 Case Description

The case description is developed from a mix of qualitative and quantitative data. The case opens up for detailed *explorative study*, where processes that have large potential for improvements are identified. These processes are then subject to further research that will eventually result in the framework design.

3.4.5 Simulation Study

Some concepts will be evaluated from simulation studies. Simulation is a special type of *experimental study*, where a computer model is created to reflect the real situation. This experimental approach is often the only possible way to gain understanding of complex interrelationships and to study the consequence of various proposed solutions.

3.4.6 Framework Design

The framework systematically describes the concepts required to achieve a strategic and value driven support organization. It is important that the concepts are general, since they should apply to any type of public transport system. The concepts are developed from *explanatory* and *normative* reasoning.

Established theories along with the collected maintenance data and the information gathered from the interviews will constitute the key input for the analysis. The framework will embrace concepts from many different theories, where each theory contributes with a different perspective.

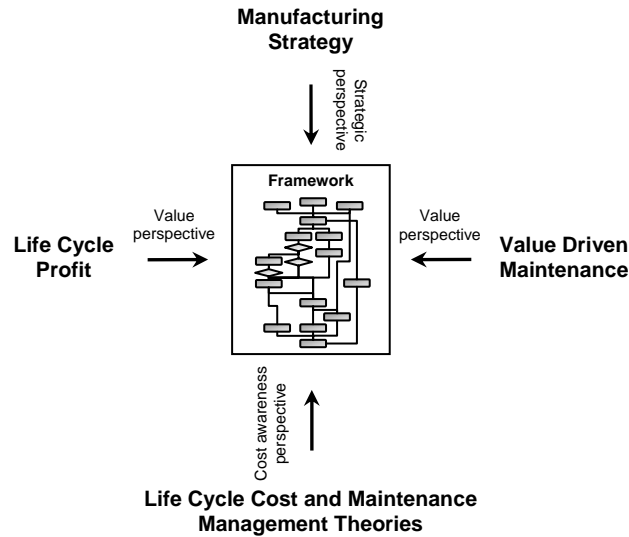


Figure 3-1: Theories making up the framework.

4 Theory

4.1 The Life Cycle Concept

The idea of the life cycle concept is that any long-term decision should be made with a whole life perspective. This means that the decision maker cannot make long-term decisions solely based on the current situation, but must also consider the future implication of the decision. The life cycle concept is traditionally used in the acquisition of complex and expensive systems. However the whole life perspective applies to a wider field of application, for example the development of a maintenance organization.

4.1.1 Life Cycle Cost

The objective of the LCC analysis is to not only look at the acquisition cost of a system, but take into consideration the total cost of ownership of a system throughout its lifetime. The LCC theory was developed by the US military already in the late 1960s, and can be seen as the first investment that emphasizes the importance of a whole life perspective⁽¹⁹⁾.

The acquisition a complex system will of course entail large ownership costs. The LCC concept illustrates this with a ship approaching an iceberg, where the tip of the iceberg corresponds to the visible acquisition cost, while the large cost of ownership is invisible beneath the water surface. The cost of ownership typically involves:

- research and development costs
- operational costs - energy consumption, operators etc.
- training of personnel
- maintenance costs – spare parts, maintenance personnel, facilities and equipment etc.
- documentation of systems and processes

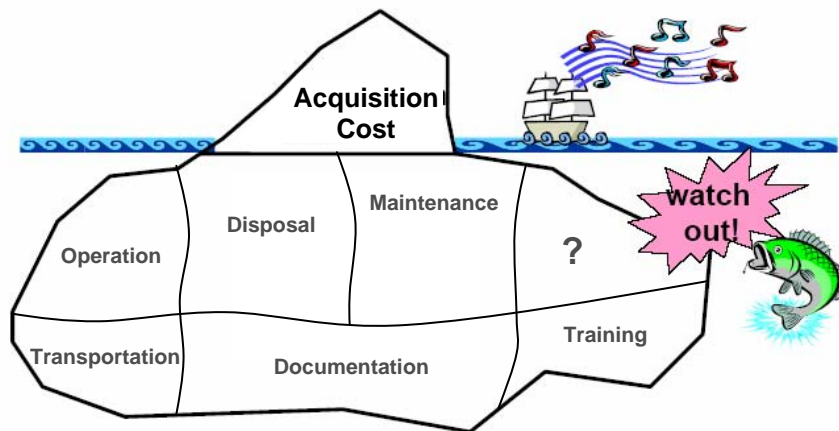


Figure 4-1: Iceberg illustrating the LCC concept (developed from Kawauchi et al, 1999).

The general LCC formula is written as:

$$LCC = LAC + LOC + LSC + LDC$$

LCC is a very comprehensive theory that expresses the overall objective of finding the most cost effective solution over a life cycle. The LCC concept embraces a large set of underlying theories that provide the means to meet this objective. A complete LCC analysis will likely include analyses such as, Integrated Logistic Support analysis (ILS), Reliability-Availability-Maintainability (RAM) analysis, economic analysis, risk analysis etc^(5,6,19).

4.1.2 Life Cycle Profit

When the LCC theory was transferred from the military context to an industrial application it was evident that the theory is shortcoming on one important matter, namely that the purpose of industrial acquisitions is to support the business concept. In this case the LCC analysis will only reveal information on one side of the business – the cost side. Thus the Life Cycle Profit (LCP) theory was developed to extend the original LCC concept to also include the revenue generating activities in the analysis.

In the LCP analysis, the contribution from revenue generating activities is often represented as non realized revenue. This is illustrated in the cigar curve where asset utilization is plotted against time and cost, and 100% asset utilization means that there is no non realized revenue. Since the organization's profitability is depending on both what is coming into and what is going out of the organization in terms of capital and resources, the decision maker must find the optimal balance between asset utilization and cost.

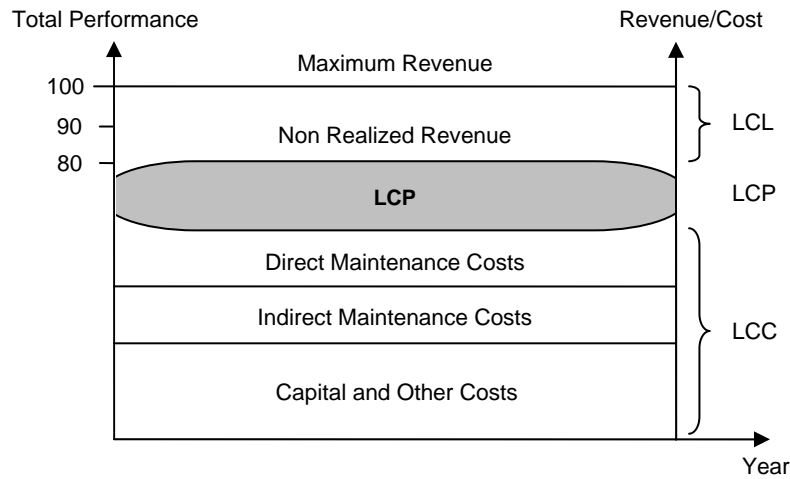


Figure 4-2: The LCP cigar curve (Ahlmann, 2002).

The general LCP formula is written as:

$$\text{LCP} = \text{LCR} - \text{LAC} - \text{LOC} - \text{LSC} - \text{LDC}$$

LCP, just like LCC, is comprehensive and includes a set of theories aimed to facilitate the analysis of revenue generating businesses, for example, the du Pont scheme and the Balanced Scorecard (BSC). The du Pont scheme is used to analyze how asset utilization, maintenance costs, and operational costs influence the profitability. The Balanced Scorecard links internal efficiency to external efficiency, and shows how they both contribute to the realization of the business concept^(1,3,11).

4.1.3 Cost/Revenue Breakdown Structure

The purpose of performing a Cost Breakdown Structure (CBS) is to identify and structure all elements that should be included in the LCC analysis. Cost elements that have a negligible impact on the final LCC result should be disregarded in the CBS in order to simplify the analysis. When performing an LCP analysis, the breakdown process must also consider revenue elements, i.e. a Revenue Breakdown Structure (RBS).

The exact content of the breakdown structure will vary from case to case depending on the purpose of the analysis and the properties of the system, but the elements in the highest CBS level are the same in most cases. These elements are: acquisition costs, operating costs, maintenance costs, and disposal costs.

In order to facilitate and standardize the LCC analysis, most industries have developed CBS templates tailored to specific LCC cases. The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology (SINTEF) has designed a CBS template for railway maintenance (Appendix I). The template includes all the significant cost elements for a railway LCC analysis, but it does not incorporate any revenue elements. A modified version of SINTEF's CBS template is recommended in this thesis. This modified version uses LCP terminology and includes the major revenue elements^(6,19).

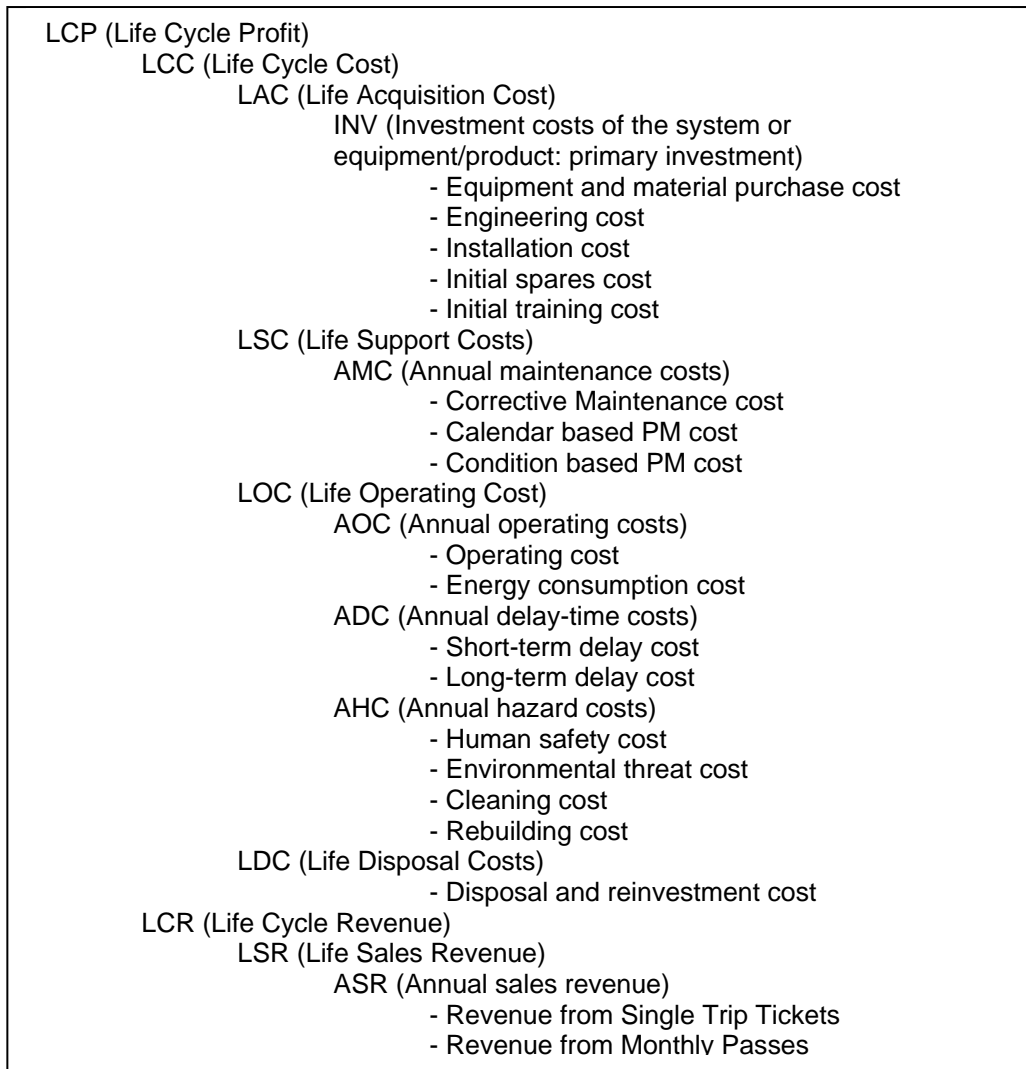


Figure 4-3: Cost/revenue breakdown structure for railway maintenance (developed from SINTEF).

4.1.4 When to Use LCC and LCP?

The LCP approach is clearly better suited for revenue generating organizations, and will never be insufficient (compared to LCC) since it encompasses everything in the LCC concept. On the other hand it includes more parameters, and thus requires more work and input information. Hence if the LCC analysis provides enough information for the decision making, it would be a waste of both time and resources to do a complete LCP analysis. Ahlmann (2002) suggests a

model for when to use LCC and LCP based on the environment the organization is acting in. If the environment is stable and predictable, the organization should focus on internal efficiency and cost, which calls for the LCC approach. If the environment is dynamic and complex, the organization should focus on external efficiency and revenue, which calls for the LCP approach⁽¹⁾.

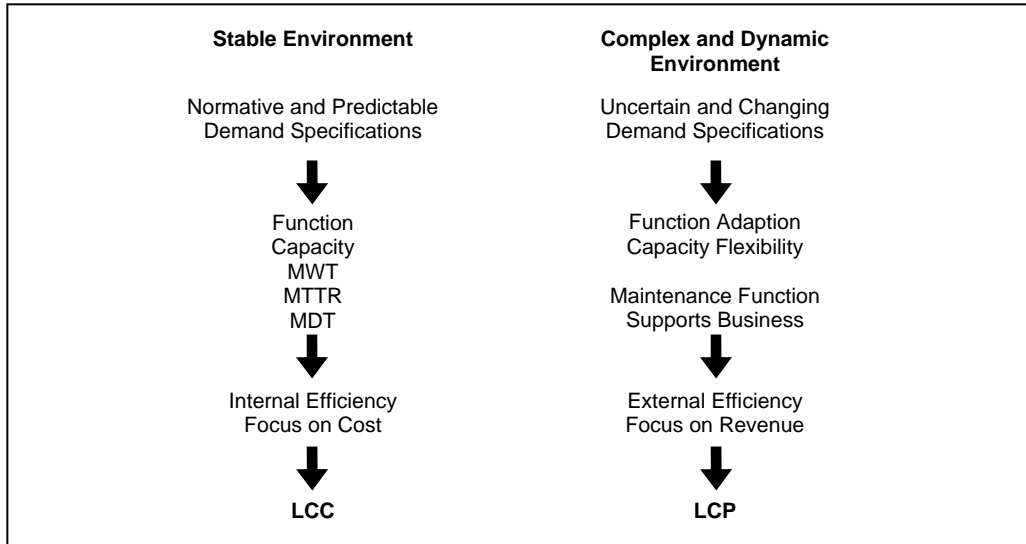


Figure 4-4: Situation linked life cycle models (developed from Ahlmann, 2002).

4.2 Value Driven Maintenance

Value Driven Maintenance (VDM) provides a view on maintenance that is similar to that of LCP. Central to VDM is that maintenance is value adding and that the maintenance management should change focus from cost to value. VDM identifies four main value drives in a maintenance organization: asset utilization, cost control, resource allocation, and Safety, Health and Environment (SHE).

Increased asset utilization is a substantial value driver, since it reduces the non-realized revenue resulting from lost ticket sales and penalty fees to passengers.

Cost control is considered an important value driver, since decreased maintenance costs will raise the profit margin, and thus create more value to the organization.

Better resource allocation has a twofold value adding effect. Firstly it cuts the costs by eliminating superfluous resources, for example, oversized inventory, unnecessary personnel and tools. Secondly it supports higher asset utilization since higher resource availability will reduce the time waiting for resources, and thus increase the asset utilization.

Safety, health and environment issues are usually connected to industry, political or judicial regulations and laws. This means that not meeting the SHE regulations may jeopardize the survival of the organization, and with that its possibility to create any value whatsoever.

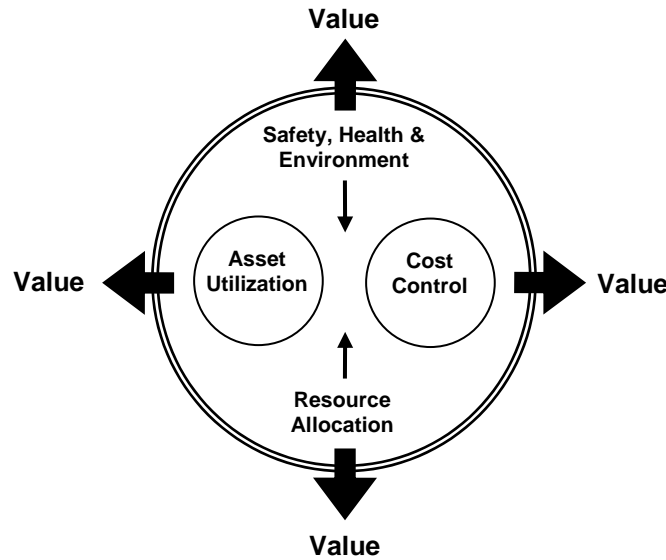


Figure 4-5: Value Drivers in Maintenance (Haarman et al, 2004)

While the LCP concept is derived from an engineering perspective, VDM uses more of a business approach to maintenance management. The VDM formula corresponding to the LCP formula is written as:

$$NPV_{\text{maintenance}} = \sum \{(-ACF_{AU,t} - ACF_{CC,t} - ACF_{RA,t} - ACF_{SHE,t}) + \sum F_{SHE,t} * (CF_{AU,t} + CF_{CC,t} + CF_{RA,t} + CF_{SHE,t}) / (1+r)^t\}$$

In the VDM formula CF and ACF stands for Cash Flow and Additional Cash Flow. AU, CC, RA and SHE are short forms of the four main value drivers.

In addition to the value driver concept, VDM also covers the identification of core maintenance competencies and significant KPIs, as well as a structured system for benchmarking against other similar organizations⁽¹⁰⁾.

4.3 Maintenance Context

One of the most important performance indicators of a system is its operational availability, which measures the systems ability to accomplish its operational plan. Operational availability is expressed as a function of reliability, maintainability and supportability. Reliability and maintainability are parameters that refer to properties of the system, while supportability regards the capability of the maintenance organization.

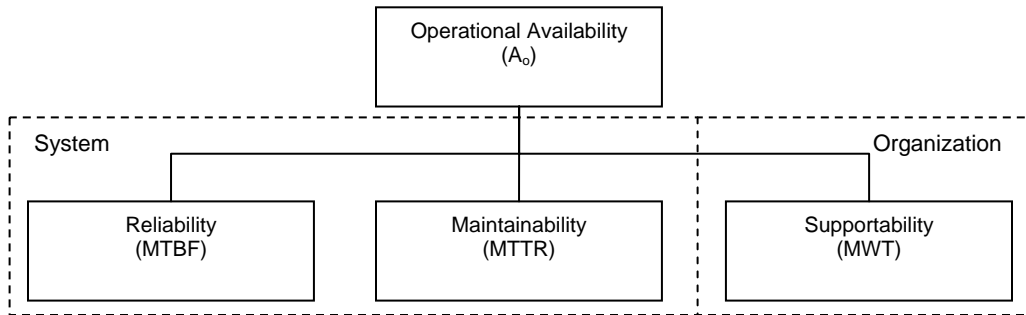


Figure 4-6: Fundamental maintenance concepts.

4.3.1 Availability

Availability measures the probability that the system will be ready or available for operation when required. There are three commonly used measures of the availability: inherent availability, achieved availability, and operational availability.

Inherent availability (A_i) is the probability that the system will be ready or available for operation when required, assuming an ideal support environment. In this scenario the maintenance downtime only includes the repair time for corrective maintenance. The inherent availability is expressed as:

$$A_i = \frac{MTBF}{MTBF + \overline{Mct}}$$

where \overline{Mct} is the corrective maintenance time.

Achieved availability (A_a) is the probability that the system will be ready or available for operation when required, including all active maintenance time (corrective and preventive). The achieved availability is expressed as:

$$A_a = \frac{MTBM}{MTBM + \overline{M}}$$

where \overline{M} is the mean active maintenance time.

Operational availability (A_o) is the probability that the system will be ready or available for operation in a real-life environment. This availability measure considers the total maintenance downtime, i.e. both the active maintenance time and the time waiting for maintenance. A_o is the preferred availability measure when assessing a system in a realistic operational environment. The operational availability is expressed as:

$$A_o = \frac{MTBM}{MTBM + \overline{MDT}}$$

where MDT is the Mean Down Time ($MDT = MTTR + MWT$)^(6,18).

4.3.2 Reliability

Reliability concerns the inherent properties of the equipment. It measures the failure frequency of the equipment, which is often expressed as the Mean Time Between Failure (MTBF) or Mean Time To Failure (MTTF). Equipment on vehicles often has a failure rate related to the distance the vehicle has traveled. In this case the failure rate is expressed as the Mean Distance Between Failure (MDBF) or the Mean Distance To Failure (MDTF)^(6,18).

Reliability has a large impact on the systems overall profitability, and it is extremely important to consider this aspect already in the early stages of the design process. Designing equipment with high failure resistance will greatly reduce the corrective maintenance costs and also increase the overall asset utilization. Robust design is one concept that stresses the importance of designing equipment with high failure resistance.

Preventive maintenance can for some equipment have a positive effect on the reliability. Although introducing preventive maintenance should be carefully considered, since preventive maintenance on functioning equipment may induce new failures.

4.3.3 Maintainability

Maintainability concerns the possibility to perform maintenance on the equipment. This is measured as the Mean Time To Repair (MTTR). A system with high maintainability will have shorter repair times and probably require less specialized tools and personnel. It is important to consider maintainability in the design process, and the concept “design for maintainability” emphasizes this^(6,18).

4.3.4 Supportability

Supportability regards the maintenance organizations’ ability to perform maintenance. This is measured as the Mean Waiting Time (MWT). MWT can be broken down into the Mean Logistics Down Time (MLDT) and the Administrative Delay Time (ADL). MLDT is the queue time waiting for required maintenance resources, and ADL is the time necessary for administrative procedures, for example, failure registration. Increasing the supportability should be a main focus for the maintenance management. This is achieved with effective administration procedures and optimal planning and allocation of the maintenance resources^(6,18).

4.3.5 Corrective Maintenance

Corrective Maintenance (CM) is carried out to restore the system functionality when failures occur. Failures are usually categorized as critical or non-critical. In case of a critical failure, the system is not allowed to continue operating, and corrective maintenance must be performed without any scheduling possibilities. In case of a non-critical failure, the system is allowed to complete its current operation and the maintenance planner have some possibilities to schedule the corrective maintenance and make sure that all necessary resources are available. Activities

in the corrective maintenance cycle are failure localization, removal of the faulty component, repair or replacement, checkout and verification of functionality⁽⁶⁾.

4.3.6 Preventive Maintenance

The purpose of Preventive Maintenance (PM) is to retain the systems condition, in order to prevent failures from happening. This includes component replacements, calibrations etc. Preventive maintenance is scheduled on fixed intervals or condition based. The intervals could either be time based or based on some other parameter, such as, for example, distance traveled. The condition of a component is either measured through human inspections or monitored by sensors⁽⁶⁾.

4.3.7 Balanced Maintenance

Systems that do not operate continuously will have periods when maintenance can be performed without affecting the operational availability, and accordingly the asset utilization. The idea with balanced maintenance is to plan the maintenance activities within these non-operational periods. Balanced maintenance is an effective way of increasing the systems availability, but it may not always be possible to realize it due to other concerns, for example, union agreements on the maintenance staffs' working hours.

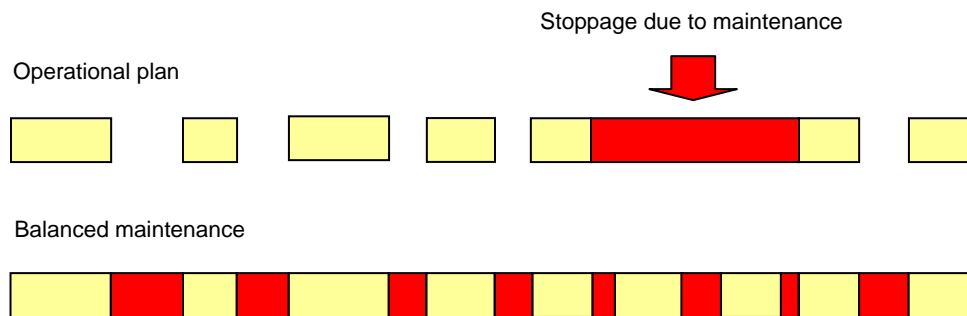


Figure 4-7: Balanced maintenance.

4.3.8 Integrated Logistic Support

Integrated Logistic Support (ILS) is a management view that focuses on controlling the planning, development and operation of a system. The purpose of ILS is to ensure that the end customer is provided with a system that meets the performance requirements, and can efficiently be supported throughout its life cycle. The integration of support elements and other system requirements is an important aspect of the ILS concept. The ILS focus is shifting with the life cycle phases of the system (i.e. evaluation of alternative systems, acquisition, and operation). During the evaluation of alternative systems the focus is to influence the manufacturer to consider aspects like reliability and maintainability in the design process. As the acquisition decision is taken, the focus is changing to evaluation of the support needs and provisioning of the necessary support elements. Finally when the system is operating the focus is to plan and provide the support⁽⁶⁾.

5 The Public Transport Case and Systecon's Engagement

5.1 Background

A transit authority has acquired 30 new commuter trains to gradually replace the current train fleet. The new trains will be delivered over a period of two years.

The new vehicles must meet demands for high reliability and low operational cost. This entails high expectations on the manufacturer to meet the performance requirements and on the maintenance organization to achieve the required availability.

The transit authority has the exclusive right and responsibility to provide public transport in the area. The company owns all the vehicles, maintenance facilities, tools etc, and a private contractor is hired to operate the traffic and maintain the vehicles.

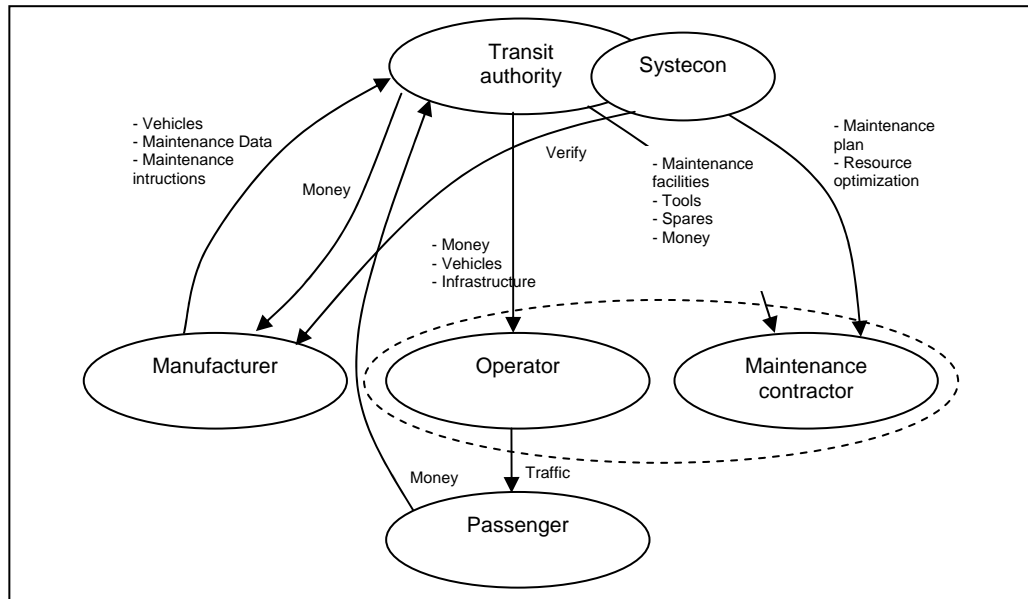


Figure 5-1: Organizational set-up and flow of resources.

5.2 The Scope of Systecon's Engagement

Systecon is engaged to assist the transit authority in developing and implementing a support strategy for the new trains. Systecon is also involved in the verification of the requirements stated in the contract. The undertaking includes:

- Review of maintenance related agreements

The Support Organization: A Strategic and Value Adding Force

- Review of maintenance data
- Definition of a maintenance concept
- Development and implementation of a maintenance plan
- RAM verification

The documentation in an acquisition of complex systems, like transit vehicles, is very extensive, and describes in great detail each of the stakeholder's duties and obligations. The public transport case described in this chapter summarizes the parts of the agreement that are most central to the development of the support organization, as well as how the maintenance data is derived, and how the maintenance guidelines have been drawn up.

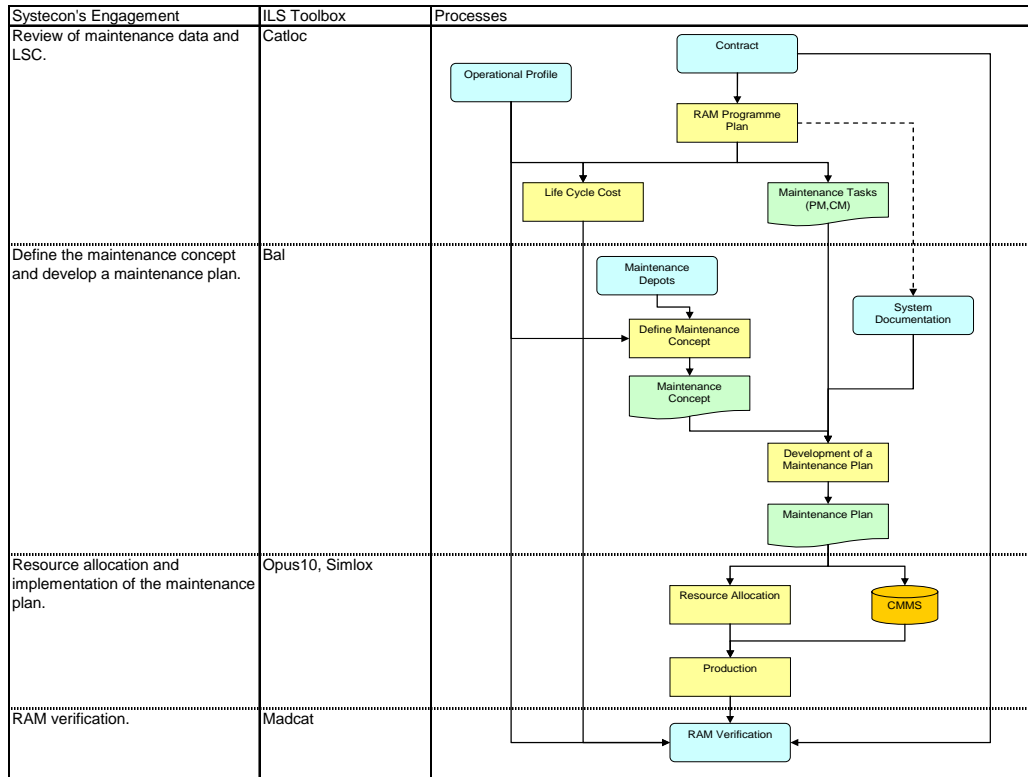


Figure 5-2: Systecon's engagement.

5.3 Review of Maintenance Related Agreements

All the responsibilities that the transit authority and the supplier have agreed to fulfill are specified in the contract. Some important areas covered in the contract are price, time and place of delivery, reliability and support costs.

The guaranteed reliability is expressed in the contract as the maximum allowed number of *stopping faults* and *non-stopping faults* per vehicle per million operating kilometers. Stopping

faults are defined as faults that cause a delay of more than 10 minutes, or faults where the vehicle must be taken out of operation after the passengers have been evacuated. Non-stopping faults are defined as faults that occur during operation and cause a delay of between 2 and 10 minutes.

The contract also states the guaranteed upper limit for the life support cost calculated over the entire train fleet. Part of the supplier's contractual obligations is to produce a detailed LSC analysis that specifies the cost distribution between components and over time. A fine is imposed on the supplier in case the operational availability is not fulfilled or the LSC target is exceeded. The guaranteed reliability and LSC target is only valid if the trains are operated according to the agreed operational rules.

The supplier has also agreed to provide a consignment stock during the first two years of operation. The consignment stock should include all the components that the supplier considers necessary to achieve the operational availability.

Finally the transit authority has a contract option to purchase up to 25 additional trains. Hence, when developing the support strategy, it is important to take into consideration that this option could be realized.

Systecon is engaged in this process to assist in the verification of these very central performance requirements, and to determine the appropriate consignment stock levels.

5.4 Preparation of Maintenance Data

In the acquisition contract it is agreed that the supplier is responsible for the preparation of maintenance data. This includes a detailed description of the system and all the maintenance activities that should be carried out in order to maintain the vehicle's reliability. In addition to this the supplier should perform a life support cost analysis based on the maintenance data. Systecon is engaged in this process to ensure that the supplier is fulfilling these obligations, and to review the maintenance data so that it is reasonable and useful in the maintenance planning.

The system is described in two different structures with respect to function and location of equipment. Each structure provides the following valuable information to the maintenance planning:

The functional breakdown structure (FBS) describes the functionalities of the vehicle from its main function down to the lowest level of detail.

The location breakdown structure (LBS) indicates each item's physical location on the vehicle.

The Support Organization: A Strategic and Value Adding Force

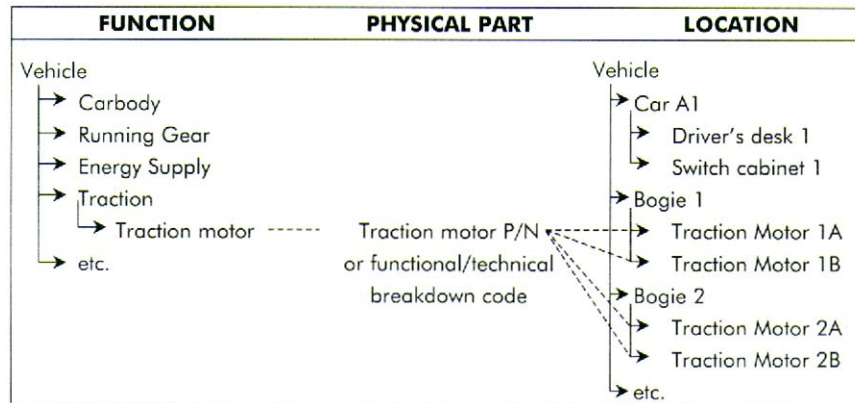


Figure 5-3: Relationship between functional and location breakdown.

The maintenance data is derived from a reliability analysis, which begins with a Failure Mode, Effects, and Criticality Analysis (FMECA) to identify failures that have significant consequences on the system's or subsystem's performance. FMECA intends to identify:

1. Failure mode
2. Failure cause
3. Failure effect on the system/subsystem
4. Criticality
5. Failure rate
6. Failure Detection Method
7. Required corrective action / Preventive or compensation action

Subsequent analyses are carried out to determine the maintenance procedures for each type of failure. These analyses consider:

- If corrective or preventive maintenance is preferred (possible preventive maintenance intervals)
- Maintenance tasks (possible preceding maintenance tasks)
- Maintenance level (e.g. vehicle, workshop)
- Personnel and skill requirement
- Spare parts
- Support equipment

In this case, the reliability analysis recognized about 900 preventive maintenance tasks and 1000 corrective maintenance tasks. The PM tasks are distributed over about 600 types of components. About 100 of these tasks are expected to take more than 1 hour, and 25 tasks are expected to take more than 4 hours. This is well in line with the guidelines in the maintenance concept. The PM interval is one year or less for 350 of the tasks, the remaining 550 tasks have a PM interval between 1.5 and 20 years.

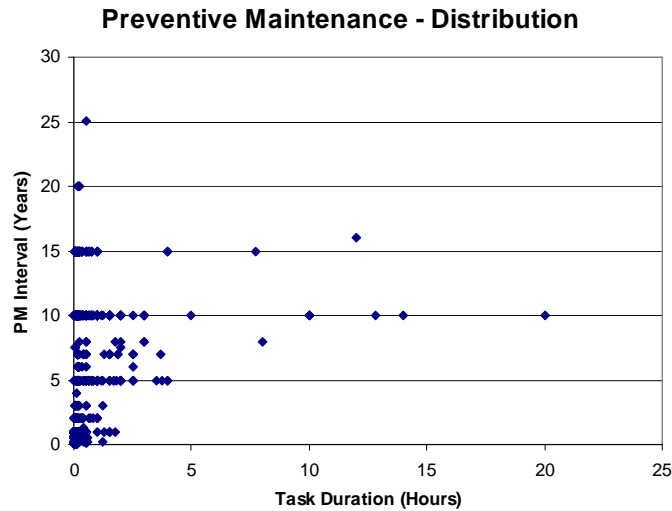


Figure 5-4: Preventive Maintenance Interval plotted against Task Duration.

The CM tasks are distributed over about 1000 types of components. About 250 of these tasks are expected to take more than 1 hour, and 50 tasks are expected to take more than 4 hours.

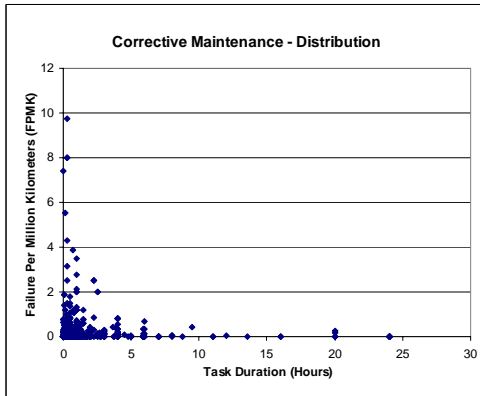


Figure 5-5: Failure Rate plotted against Task Duration

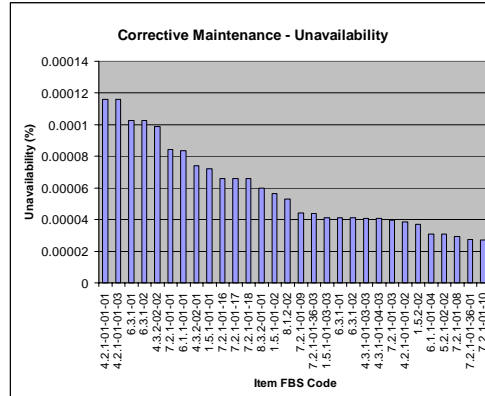


Figure 5-6: Items with high unavailability.

The supplier's life support cost analysis is conducted based on the corrective and preventive maintenance tasks identified in the reliability analysis. Maintenance costs that could not directly be connected to the inherent design properties of the vehicle are excluded from the analysis (e.g. costs due to vandalism, maloperation etc.).

The system description along with the FMECA and the subsequent analyses constitute a major input to developing the maintenance plan. Systecon has throughout the preparation process been engaged to review all maintenance data.

5.5 Definition of Maintenance Concept

The initial maintenance plan suggested by the supplier was composed of fairly large packages of maintenance tasks. This solution was shown through simulation to be incompatible with the operational profile of the vehicle, and therefore not able to meet the availability demands. To facilitate the development of a new improved maintenance plan, Systecon has defined a maintenance concept that includes:

- Classification of maintenance tasks
- A balanced maintenance strategy
- Guidelines for the packaging of preventive maintenance tasks
- Regulations on how the maintenance work should be split up between the depots.
- Handling of preventive maintenance peaks

Maintenance tasks are classified as light or heavy maintenance depending on the resources required to perform the tasks. Maintenance is permitted during certain predefined periods based on the operational profile of the vehicle. This allows for the definition of a balanced maintenance strategy, where the preventive maintenance tasks are scheduled when the vehicle is not in operation. Heavy maintenance that requires much time should be carried out in the summer, when traffic is usually low.

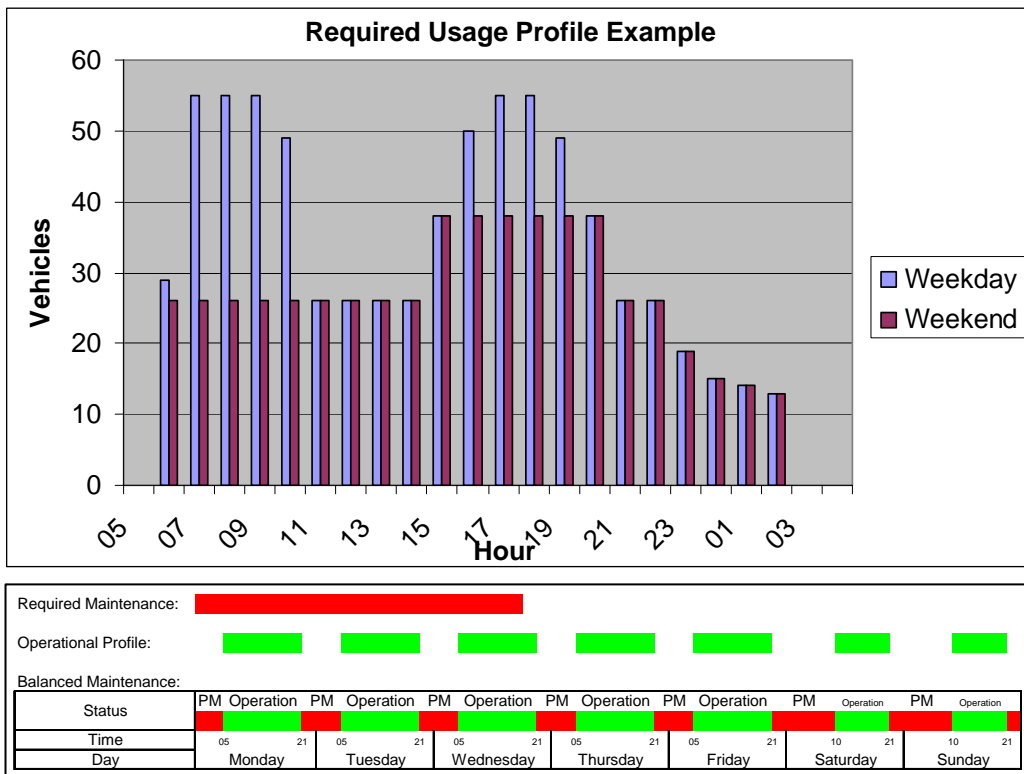


Figure 5-7: Operational profile and the corresponding balanced maintenance strategy.

The Support Organization: A Strategic and Value Adding Force

In order to make the packaging of preventive maintenance tasks flexible, it is important that each specific maintenance task is independent and can be carried out in a relatively short time. The guideline is that it should be possible to complete 98 % of the maintenance tasks in less than 4 hours, and 90 % of the maintenance tasks in less than 1 hour.

Important considerations when creating packages are:

- The time it takes to complete the maintenance task
- The preventive maintenance interval
- The item's location on the vehicle
- If special tools or skills are required

The maintenance packages should fall into one of the following categories:

- Maintenance packages that can be completed by 4 maintenance technicians in less than 4 hours. These packages are short enough to be carried out on weekdays between morning and evening rush hour.
- Maintenance packages that can be completed by 4 maintenance technicians in less than 8 hours. These packages should be scheduled on nights and weekends.
- Maintenance packages that can be completed by 4 maintenance technicians in between 8 and 16 hours. These packages should be scheduled on weekends.

The maintenance work is divided up between two depots. Light maintenance can if necessary be redirected to a third depot. Systecon has been engaged to analyze both how the vehicles should be distributed between the depots, and how many maintenance tracks that are needed at each depot to handle the workload.

A large part of the heavy preventive maintenance tasks have the same interval. This means that during some periods the workload in the maintenance organization will increase significantly. The maintenance organization will not be able to handle the workload during these peak periods, unless the organization is temporarily expanded or the preventive maintenance peaks are smoothed out over time.

5.6 Development and Implementation of Maintenance Plan

The objective when developing a maintenance plan is to arrange the maintenance tasks in packages that can be carried out with minimal effect on the operational availability.

The preventive maintenance tasks should be packaged in accordance with the guidelines stated in the maintenance concept. The objective of the packaging process is to create 30-40 maintenance packages out of the 900 PM tasks. The number of maintenance tasks and the parameters that must be considered makes packaging process very complex and difficult to overview.

The maintenance plan is used for resource allocation and maintenance planning, and consists of the maintenance concept along with the maintenance packages and the corrective maintenance. A computerized maintenance management system (CMMS) is used to apply the generic maintenance plan to each individual vehicle. Information on when the vehicle was first put into operation and the total travel distance of the vehicle is used to decide when in time the

preventive maintenance should take place. It is the maintenance supplier's responsibility to do the detailed maintenance planning based on the information available in the CMMS.

Physical resources should be allocated before the maintenance plan is implemented in the support organization. The objective of the resource allocation is to achieve the desired availability at the lowest possible cost. Important resources considered in the analysis are number of maintenance tracks at the depots, spare stock levels, and maintenance personnel.

5.7 RAM Verification

Continuous follow-up on maintenance and performance data is carried out during the first two years of operation. The verification intends to ensure that the trains meet the availability and life cycle cost requirement stated in the contract. The verification concerns failure rates, repair times, and costs.

The transit authority and the supplier have agreed on the following regulations for the verification process:

- The verification of the reliability and LSC should be limited to 15 vehicles (delivery number 6 to 20).
- The follow-up procedure should be identical for all vehicles to ensure a consistent verification.
- The verification period is 2 years or 360,000 operating kilometers per vehicle, but only the last 12 months are included in the formal verification. Hence the whole verification process will last for about 32 months.
- The verification should start after 1.5 months (20,000 kilometers) of operation. However the follow-up should start immediately after the vehicles have been put into operation.

Data is collected from various sources and stored in the CMMS. The operators report traffic interruptions. The maintenance personnel register failures and completed maintenance. Delays are verified against the traffic controller.

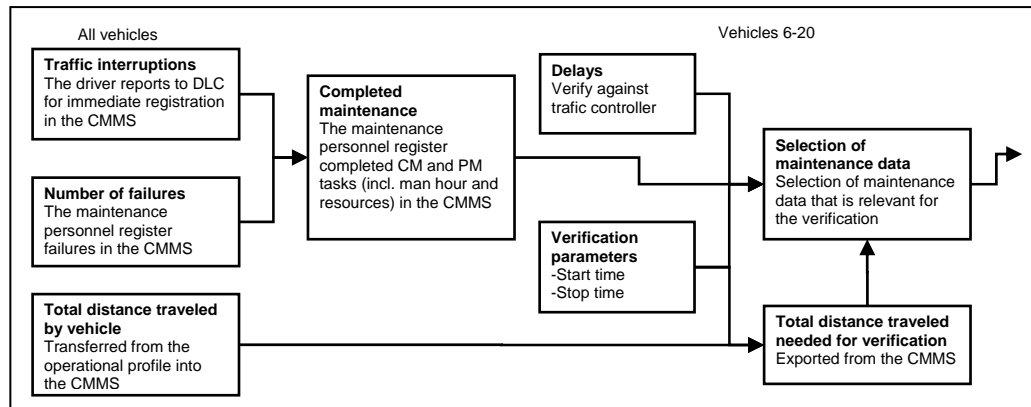


Figure 5-8: The data gathering process.

6 Linking Strategic and Value Driven Theories to the Public Transport Case

The public transport case described in the previous chapter shows that most of the analyses are based on traditional LCC and logistic support concepts. The LCC and logistic support theories were originally developed and used by organizations with the main objective to meet targets at the lowest cost possible. Hence these theories have a strong focus on cost effectiveness. This focus is not sufficient when designing the support organization for a public transport system, since profitability and corporate strategy are important aspects that must also be considered. Hence, this approach must be extended to embrace the support organization's full potential as a strategic and value adding force. Chapter 7 presents a framework for developing a strategic and value driven support organization. The framework describes a cycle of activities intended to create the desired support organization. The extended approach described in the framework should be implemented with Systecon's software suite, which is described in chapter 8.

Before the framework is presented, this section introduces some central strategic and profit driven theories and explains how they apply to the public transport case. This includes a short explanation of how production management thinking could be applied to a public transport maintenance organization, and how the life cycle profit concept spans across the organization and over time.

6.1 *Public Transport Maintenance from a Manufacturing Strategy Perspective*

Passengers using public transport buy a service that will take them from one location to another. The public transport company is delivers this service by providing a transit system including infrastructure, vehicles, and operators etc. Only as a whole system are these elements of value to the customers (i.e. the passengers). This means, assuming the infrastructure is permanent, that in order for the service to be delivered as promised, a vehicle and an operator must be present at the departure station on time.

The operator and the maintenance supplier have a shared responsibility in the commitment to the passengers. The operator is responsible of operating the vehicles and the maintenance supplier is responsible of ensuring that vehicles are ready for operation in accordance with the timetable. This implies that the support organization's performance has immediate impact on whether or not the service will be delivered to the customers. In most situations the impact of a system breakdown can be minimized by using buffer stocks or by having the option to postpone the delivery time. None of these solutions work for the public transport case, since it is not financially justifiable to have spare vehicles, and the timetable must be kept. These circumstances make the public transport support system similar to a manufacturing system with a batch process, where products are assembled to order, and on-time delivery is strictly required. The corrective maintenance activities can be compared to production orders with a short delivery time, and preventive maintenance activities can be compared to production orders in the pipeline, where the planning horizon is longer. The corrective maintenance activities

The Support Organization: A Strategic and Value Adding Force

occur as discrete events, thus the support organization must be dimensioned according to forecasts based on the failure rates.

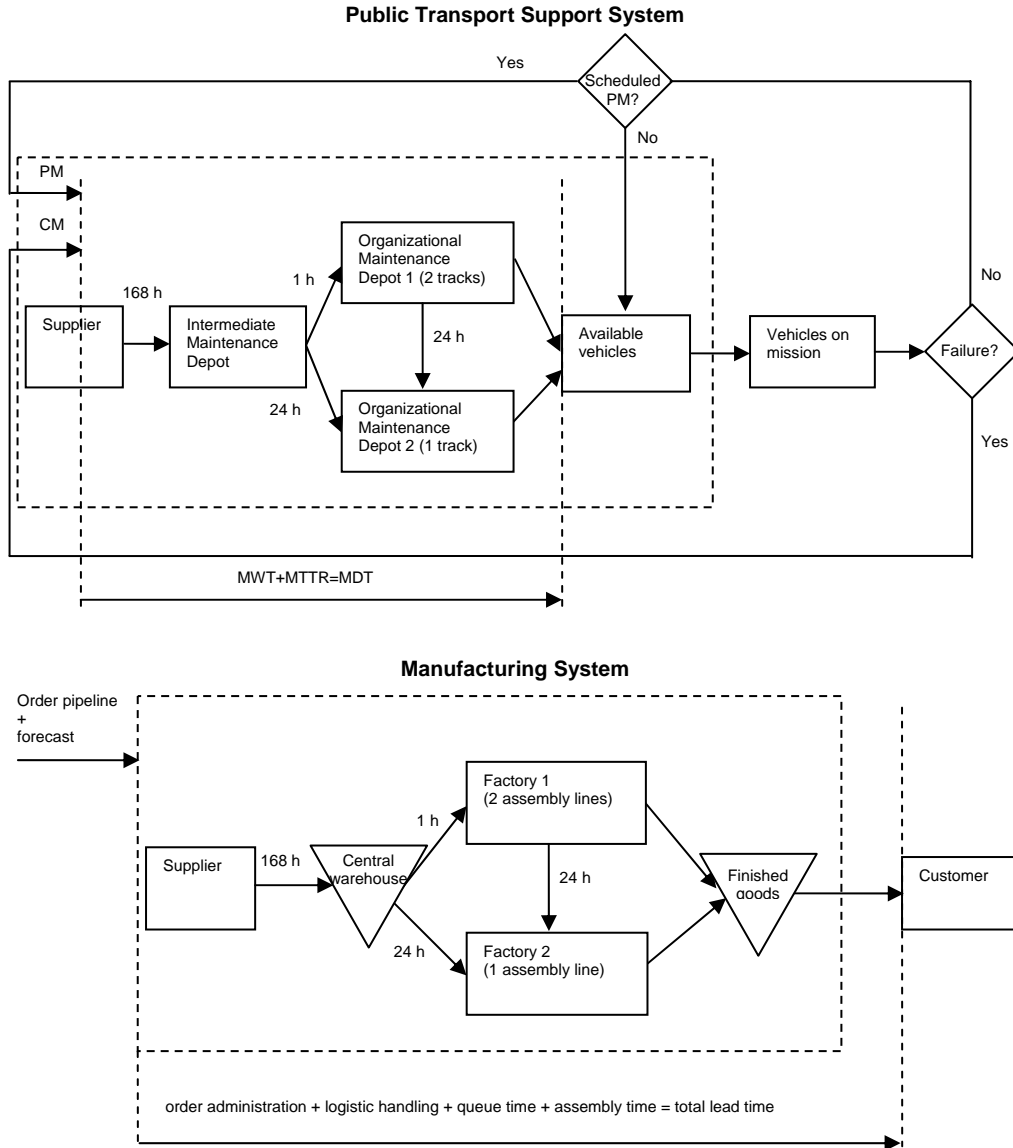


Figure 6-1: The public transport support system and a manufacturing system (batch process, assemble to order).

Hill (2000) emphasizes the manufacturing system’s strategic role. The essence of these theories is that in order to avoid sub-optimal solutions all functions within a corporation must strive to achieve the overall corporate mission⁽¹³⁾. Based on the similarity between manufacturing and maintenance, the same thinking should apply to the public transport scenario. Hence it is of interest to analyze how to incorporate production management theories when designing the maintenance organization for a public transport system.

6.2 Life Cycle Cost/Revenue Elements in the Public Transport System

The transit authority is outsourcing most of the short-term responsibilities to external contractors, while long-term planning and strategic decisions are controlled in-house. To maintain control of the organization the transit authority collects all revenues and owns all the expensive resources such as vehicles, maintenance facilities etc. The cost/revenue breakdown structure for the transit authority will, with this organizational set-up, mainly consist of outsourcing costs and investments in strategic resources.

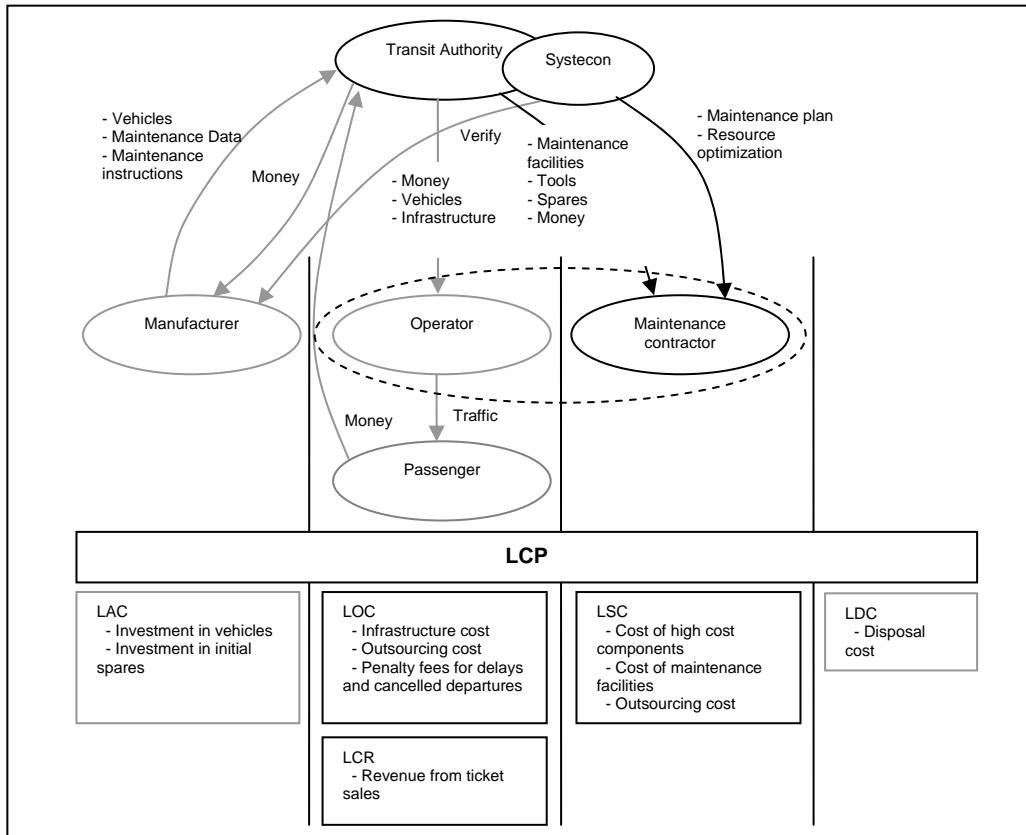


Figure 6-2: Life Cycle Cost/Revenue elements linked to stakeholders.

6.3 The Commuter Vehicles' Life Cycle Phases

The commuter vehicles will go through four major life cycle phases – evaluation, acquisition, operation, and phase out. The cost and revenue streams generated by the vehicles will vary across these phases, as will the focus of the maintenance management. Blanchard (1981) describes in the ILS concept how the focus of the maintenance management changes over time.

The life cycle starts with the evaluation phase, where alternative systems are evaluated against the predefined requirements. This phase involves no large cost streams, but major future cost and revenue streams are to great extent established at this stage. The maintenance management focus should thus be on influencing the system design to facilitate future profitably.

The second phase is the acquisition of the systems. The management focus should be evaluation of the support needs of the systems and provisioning of the support elements.

System operation is the phase where the investment starts paying off. The maintenance organization should in this phase plan and provide the support necessary to extract maximum profitability from the systems.

The public transport case described in the previous chapter is currently in the life cycle phase where the vehicles successively are being delivered and taken into operation. The evaluation of the support needs and the provisioning of the support elements is still in progress, at the same time the planning and providing of support has just started.

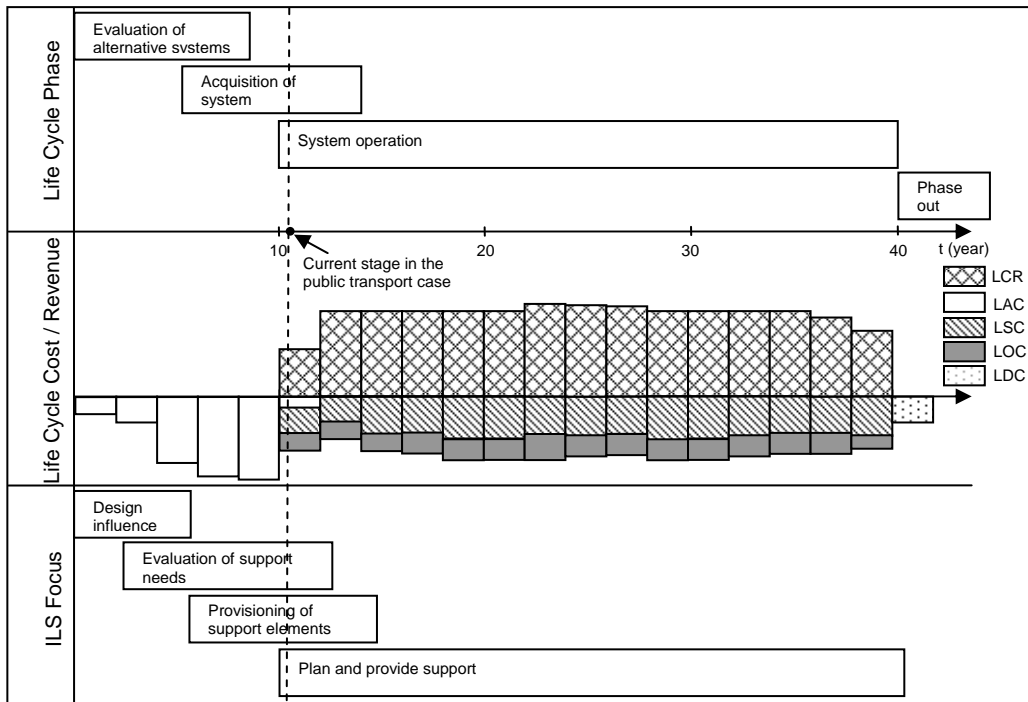


Figure 6-3: The commuter vehicles' life cycle phases and the corresponding ILS Focus.

7 Framework for Developing a Strategic and Value Driven Support Organization

In a public transport system there is no possibility to make up for lost traffic production, and cancelled traffic will result in both economic and goodwill loss. This makes the public transport system particularly vulnerable to disturbances in the maintenance organization. Säby's model for classification of various maintenance situations perfectly illustrates the public transport system's exposed position⁽²⁴⁾.

Production \ Market	No market reaction, but less volume to sell	Economic and goodwill loss
Disturbances are handled by the production process		
Possibility to make up for disturbances through overtime etc.		
Disturbances result in loss of traffic production		Public Transport System

Figure 7-1: The impact of disturbances on the public transport system's internal and external effectiveness (developed from Säby, 1984).

Thus when designing the support organization for a transit system, the following characteristics must be central to the analysis:

- Public transport companies act in a competitive environment
- Public transport is a revenue generating business
- The complexity of the system and its environment

This calls for the LCP and VDM concepts to be used to extend the traditional LCC approach. In addition to this a strategic focus should pervade the entire design process. With this extended approach the support organization is not only viewed as a function necessary to maintain the system, but also as an important strategic force to achieve the overall corporate mission.

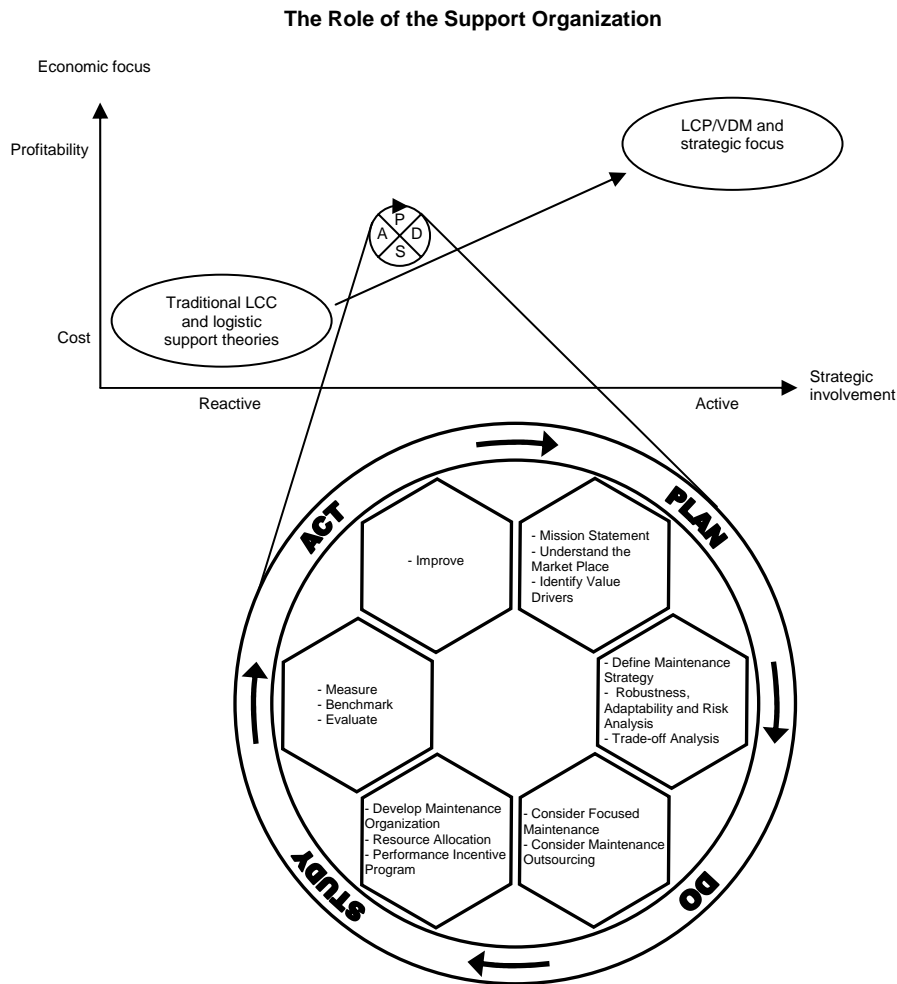


Figure 7-2: Expanding the role of the support organization.

The transition to a strategic and value driven support organization is a continuous process. Accordingly the framework presented in this chapter builds on the continuous improvement cycle, also known as the Plan-Do-Study-Act (PDSA) cycle.

The development of a strategic and value driven support organization requires a top-down approach beginning with the corporate mission statement and ending at the smallest sub-functions. The implementation and improvement process however requires a bottom-up approach beginning at the lowest functional level and ending at the top management level.

One important area that is not covered in this framework is the short-term planning and execution of the maintenance tasks, since this goes beyond the delimitations of this thesis.

The Support Organization: A Strategic and Value Adding Force

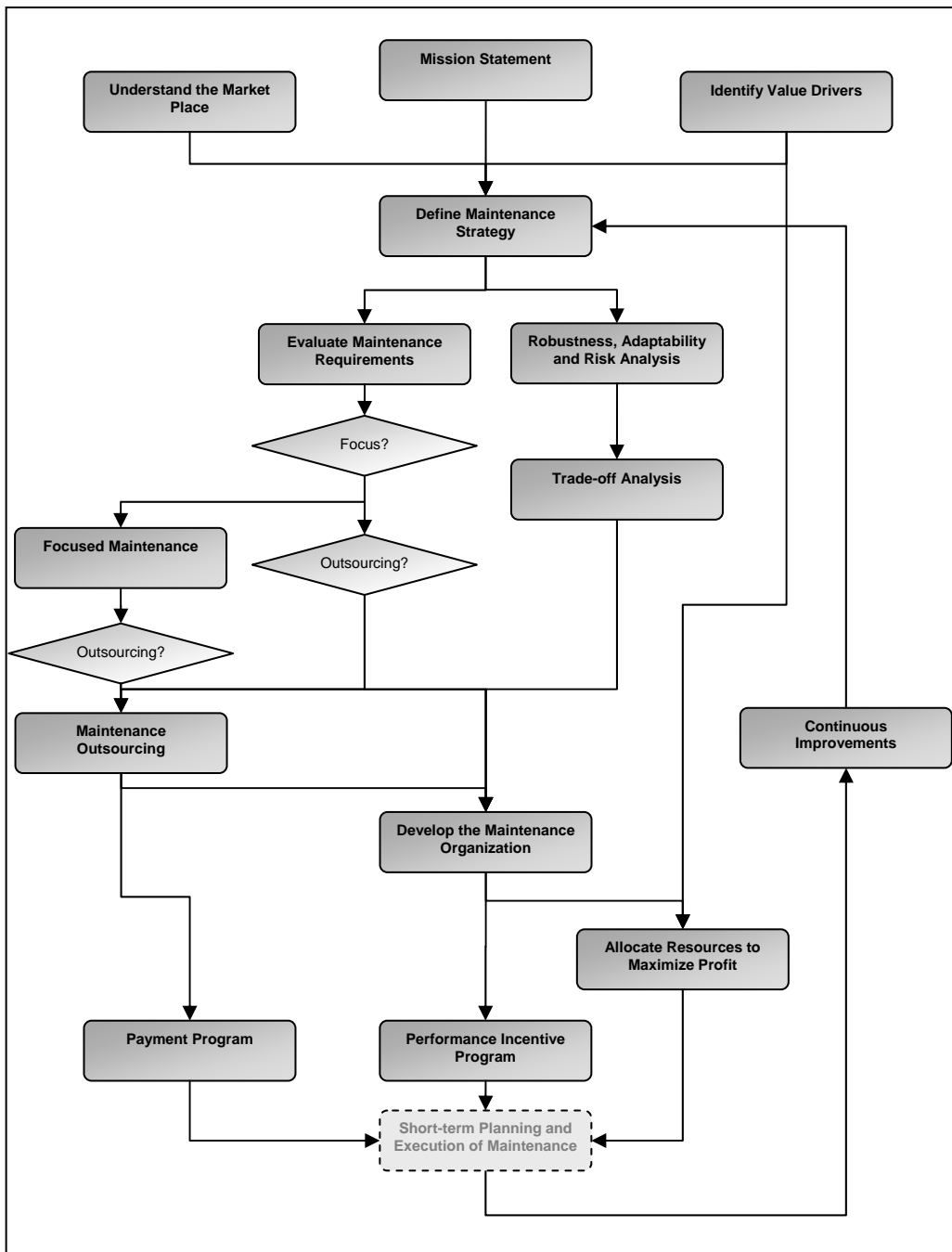


Figure 7-3: The framework for developing a strategic and profit driven support organization.

7.1 Mission Statement

All organizations should have an overall organizational strategy, which is expressed in the mission statement. The mission will obviously vary between organizations, but the purpose is the same, namely, to set out the direction in which the organization aims to move. Every function within the organization should then be moving in the agreed direction. Hence the mission statement is central input when defining the maintenance strategy, which is described in section 7.4.

7.2 Understand the Market Place

Understanding the market place is one of the keys to developing a strategic maintenance organization. This involves recognizing the competing alternatives as well as learning about the customers' preferences.

The main competitor to public commuter transport is car traffic. The two competing alternatives have different pros and cons. Public transport is a better economic and environmentally friendly alternative and may also be faster in an urban area with heavy traffic congestion. Cars on the other hand are more flexible.

The passengers' preferences are fundamental, since decisions should be made in the best interests of the passengers. Hence it is crucial to learn about the passengers' preferences. This information can be obtained from surveys and observations of the passengers' behavior. Observing the passengers' behavior is often the most accurate way to obtain information about what the passengers actually demand, since the passenger may say one thing in surveys but it is how they act that really matters. It is not always possible to comply with every request, and therefore it is important to understand what the passengers' value the most. Techniques on how to obtain this information are essential for the analysis, but they will not be discussed further in this thesis.

Hill (2000) suggests a classification system for linking manufacturing to the market. Product criteria are divided into the following three categories based on their competitive importance on the market⁽¹³⁾:

- *Order winners* are those criteria that win orders on the market. These criteria explain why the customers choose one specific product from a set of competing alternatives.
- *Qualifiers* are criteria that must be met in order for the customer to consider the supplier. The difference between qualifiers and order winners is that with qualifiers organizations need only to be as good as the competitors, while with order winners organizations must be better than its competitors.
- *Order-losing criteria* are those that if they are not at an acceptable level the order will fail even if order winners and qualifiers are met.

The same classification system could be used for linking maintenance criteria to the market. In the public transport case the criteria should be compared with the main competitor, i.e. car traffic. The criteria could, for example, concern price, availability, safety etc. In that case price and availability may be order winners, since the customer will only choose public transport if it is an economic and reliable alternative to road traffic. Safety is a typical qualifier, which means

The Support Organization: A Strategic and Value Adding Force

that the transportation must be safe in order for the customers to even consider public transport. Finally inadequate traveling experience and security could discourage people from traveling by public transport.

	Order winner	Qualifier	Order loser
Price	X		
Availability	X		
Convenience	X		
Safety (against accidents)		X	
Environmental friendliness		X	
Traveling experience			X
Security (against crime)			X

Figure 7-4: Linking maintenance to the market.

Of the above mentioned criteria price, availability and safety are those the maintenance organization can influence the most. Traveling experience and security are criteria that mainly concern the operator.

7.3 Identify Value Drivers

According to Ahlmann (2002), the total value created by an organization is the product of the internal efficiency and external efficiency, if these are simultaneously acting. This can be expressed as⁽¹⁾:

$$\text{Total Effectiveness} = \text{Internal Effectiveness} \times \text{External Effectiveness}$$

The value driver analysis is carried out to identify those maintenance processes that influence total effectiveness the most. A suitable basis for this analysis is the four value driver categories in VDM: asset utilization, cost control, resource allocation, and safety, health and environment (SHE). In the public transport case, cost control and resource allocation concern internal effectiveness, while asset utilization and SHE concern external efficiency^(1,10).

The most significant value drivers are those that have a twofold effect on the effectiveness. Enhancing these value drivers will raise both the internal and the external efficiency simultaneously, and thus create a multiplicative increase of the total effectiveness⁽¹⁾.

In the value driver analysis it is important to watch out for value killers. An improvement with positive effect on the internal efficiency may sometimes simultaneous lead to a larger negative effect on the external efficiency, or vice versa. In this case, what is supposed to be a value adding improvement turns out to be a value killer.

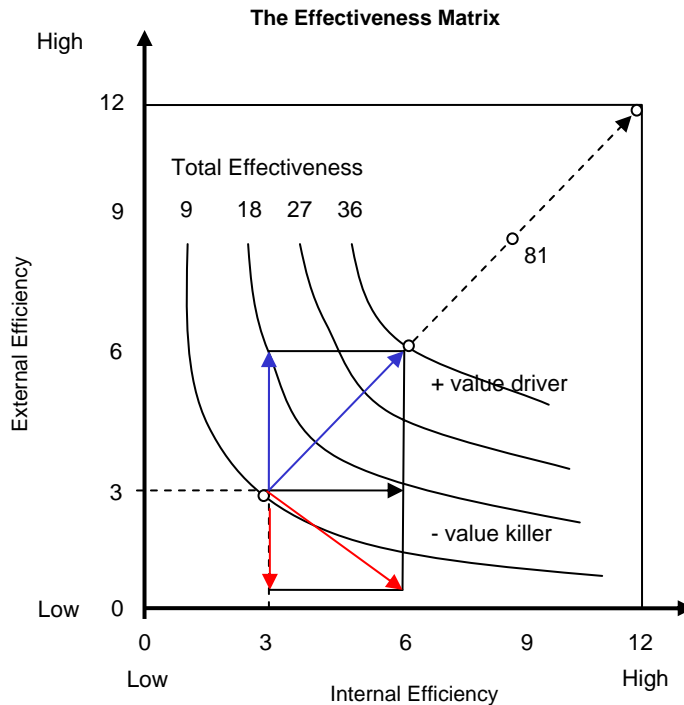


Figure 7-5: The effectiveness matrix showing the outcome of a change on the total effectiveness for both a value adding improvement and a value killing “improvement” (Ahlmann, 2002).

The following example explains the value driver/value killer concept:

A public transport company has 90% operational availability of the train fleet. The maintenance organization currently has a 5 million Euro budget. The corporate management is now requesting cost cuts next year. The maintenance management team is therefore considering two options.

The first option is a cost control action where the maintenance staff is reduced with 15%. This will save 500,000 Euro per year.

The second option is resource allocation action that involves reallocation of the high cost component inventory, and selling of the superfluous components. An optimization consultant estimates that this will save 300,000 Euro per year, and at the same time increase the availability of components from 94% to 97%. Investing in an optimization tool costs 150,000 Euro.

The maintenance management team is unsure of the total effect of these two options and consults an external expert. The expert reads the latest financial report and finds that revenues generated by the train fleet add up to 19 million Euro per year. The expert estimates the value of 1% operational availability to 200,000 Euro per year. Further more, the increased availability of components is estimated to result in an increase of the operational availability to 92%, while

The Support Organization: A Strategic and Value Adding Force

reducing the maintenance staff with 15% is estimated to decrease the operational availability to 87%. Based on this the expert makes an LCP analysis on the two options.

Option 1: $LCP_1 = \text{Savings}_{\text{reduced personnel}} - \text{Lost revenue}$
 $LCP_1 = 500,000 - 3 * 200,000 = -100,000 \text{ Euro}$

Option 2: $LCP_2 = \text{Savings}_{\text{reduced stock levels}} + \text{Increased revenue} - \text{Investment}_{\text{optimization tool}}$
 $LCP_2 = 300,000 + 2 * 200,000 - 150,000 = 550,000 \text{ Euro}$

The expert shows the calculations to the maintenance management and explains that option 1 is a value killer, while option 2 is a significant value creator that increases both the internal and the external efficiency. Based on the expert's advice the management team chooses to invest in the optimization tool and implement option 2.

This example shows the importance of considering all effects of a decision in the value driver analysis.

7.4 Define Maintenance Strategy

As already mentioned in section 7.1, every function within the organization should focus on supporting the corporate mission. In many organizations this is not the reality. Instead it is common that each function develops its own strategy that is independent from the overall strategy as well as other functional strategies within the organization. In this case the organization will constitute a number of inconsistent sub-optimal functions. To avoid this, the functional strategies must be integrated with the organizational strategy⁽¹³⁾.

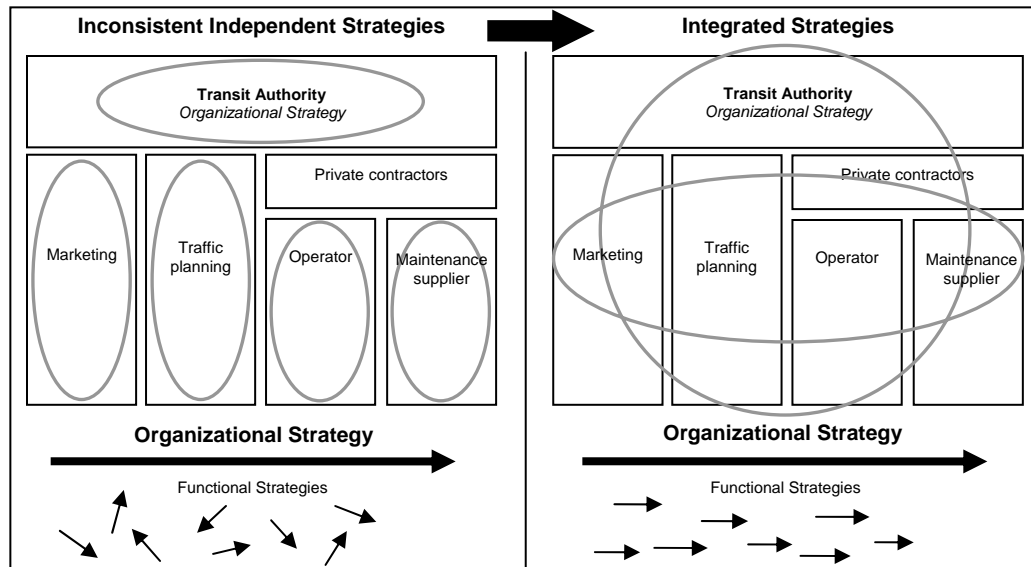


Figure 7-6: The transition from an organization of inconsistent functional strategies to an organization where all functions are moving in the agreed direction (Hill, 2002)

To define a maintenance strategy that is congruent with the overall corporate mission, the maintenance managers should first identify which objectives in the corporate mission the maintenance organization can support, and thereafter link these corporate objectives to the order winning and value adding activities.

The process of defining a maintenance strategy is further complicated in the public transport case, where private contractors, with their own corporate strategy, are responsible for some functions. The maintenance function often has one of the most complex organizational set-ups, since it is common that key responsibilities are split between several influential suppliers (e.g. the transit authority, the manufacturer, the maintenance contractor). It could be that the transit authority has responsibility for the planning, follow-up, and provisioning of expensive resources, such as facilities and equipment. For this an external maintenance consultancy firm may be engaged to support with expert knowledge. The manufacturer is responsible for managing the consignment stock of high cost strategic components, and the maintenance contractor is responsible for the short-term planning and execution of the maintenance.

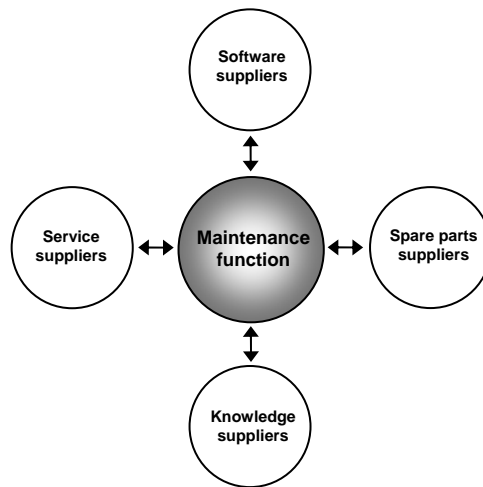


Figure 7-7: Parties influencing the maintenance function (developed from Haarman et al, 2004).

To ensure that all the involved suppliers support the maintenance strategy, the management must create tailored performance incentive programs for each supplier. A suiting performance incentive model is presented later in this chapter.

7.5 Increased Reliability through Robustness

In complex systems it is impossible to foresee every single possible disturbance and the required corresponding support action. A well thought-out maintenance program including predicted corrective maintenance and planned preventive maintenance can only partly guarantee high system reliability and availability. To further increase the reliability and availability additional actions must be taken. This includes introducing redundancies and other

measures to minimize the damages from unforeseen events. Introduction of redundancies is an effective way of increasing the reliability, since the increased cost of redundancies follows a linear function, while the increased reliability from redundancies follows an exponential function.



Figure 7-8: The relationship between the cost to establish redundancy, and the reliability resulting from redundancy (Ahlmann, 1992)

Robustness should be considered in every aspect of the system (e.g. vehicles, infrastructure, and organization). A common misconception is that maintenance cannot improve the failure resistance of a system, and that this can only be accomplished through modifications of the system (i.e. robust design). This is not entirely true since environmental circumstances, such as infrastructure, operation etc., have a large impact on a system's reliability. Thus improvements of the environmental circumstances can further increase the reliability⁽²⁾.

Aviation is a good example of a complex system with long experience from working with redundancies in order to achieve exceptionally high reliability. Aircrafts are designed to be able to complete the mission even when critical failures occur. Other complex transport systems could use the same methods to reduce the number of stopping failures and thus increase the reliability. Redundancies will however involve increased costs and the actual gain must therefore be considered carefully before redundancies are introduced⁽²⁾.

7.6 Adaptable Solutions

The purpose with design for adaptability is to look beyond today's situation and also include expected future scenarios in the analysis. This could concern political actions to increase the use of public transport, intentions to extend the night or weekend traffic, expansion of the train fleet etc.

Using design for adaptability when developing a maintenance organization means that adaptability should always be one aspect of the decision making. This does not imply that adaptable solutions always are preferred to less adaptable solutions. It is only one aspect among others. For example, if it is very unlikely that the number of passengers will decrease within the nearest future then there is no motive in investing capital on adaptability to this scenario. If instead public transport most likely will increase over the next years then it is highly motivated to promote adaptability to this scenario, as long as it is financially justifiable⁽¹⁷⁾.

In the public transport case there is an option of buying additional 25 vehicles. If this option is realized, fully or partly, it will significantly increase the maintenance workload. Hence this aspect should be included in the resource allocation process and the repair track analysis. If the repair track analysis is part of the dimensioning of a new maintenance facility then it is

reasonable to analyze how many repair tracks 25 more vehicles would require, and then design the new facility such that it can easily and inexpensively be expanded with necessary additional repair tracks. When building new maintenance facilities, it is also valuable to consider if the facilities could be built such that they could serve other purposes in case the maintenance organization decides to move out.

Adaptability is also an important aspect in the development of the maintenance concept and the packaging of maintenance tasks. This involves checking with the traffic planner whether there are any plans to extend the night or weekend traffic within the nearest future, since much of the concept and packaging guidelines relies on the operational profile of the vehicles.

7.7 Risk Analysis

The objective of a risk analysis is to identify possible hazards of a system, and the causes and consequence of these hazards. The identification process should, to begin with, include both likely and unlikely hazards as long as they are realistic. Identified hazards may then be disregarded from the subsequent analysis if the consequences are insignificant or the likelihood of occurring is negligible. This study should generate a list of all relevant hazards, and where these may occur. The next step of the risk analysis is to identify and describe the cause of each hazard. Likely causes of hazards in the public transport case are:

- Human factor (e.g. vandalism, human mistakes)
- Technical factors (e.g. malfunctioning components)
- Organizational factors (e.g. unsatisfactory maintenance routines)
- Environmental factors (e.g. natural disasters)

The risk analysis should also appraise the consequences and frequency of each hazard. In addition to this, the event chain following each incident must be identified and described. Consequences can be categorized as (a hazard can of course have consequences spanning across multiple categories):

- People (health and safety)
- Environmental
- Economical
- Operational
- Company reputation

A risk evaluation based on the consequence and frequency will reveal those hazards that are most critical. Severe consequences mean higher risk factor, and high frequency means higher risk factor⁽²³⁾.

A study of the risk situation for railway transportation in Sweden shows that public transport is generally very safe. The safety of rail traffic in Sweden has improved considerably over the last four decades, especially in connection with the introduction of an Automatic Train Control (ATC) system in 1979/80⁽⁹⁾.

The Support Organization: A Strategic and Value Adding Force

Year	Passenger Fatalities Per Year (Mean)	Passenger Fatalities Per Billion Passenger Kilometer
1961-70	11	2,1
1971-80	9,5	1,7
1981-90	2,5	0,38
1991-2000	0,8	0,12

Figure 7-9: Passengers killed in rail traffic in Sweden between 1960 and 2000 (Grimvall et al, 2003).

A political decision from 1988 regarding railway safety states that⁽⁹⁾:

“Rail traffic should be safer than any other transport system (person or cargo) in Sweden, at the same time the risk of being killed or injured in rail traffic should continuously decrease”

An addition from 1990 to this statement puts the safety issue in a somewhat different light⁽⁹⁾:

“Since rail traffic is already far safer than the competing road traffic, one should be restrictive with safety measures that have a cost driving effect that, in turn, has a negative impact on the rail traffic’s competitiveness”

The interpretation of this statement must be that further improvement of safety should not be prioritized above other important aspects such as availability and competitiveness.

Noteworthy is that this study mainly concerns the consequences on the people category (i.e. fatalities) compared to road traffic. From the support perspective it is of interest to analyze if there are hazards that have consequences on any of the other categories (i.e. environmental, economical, operational, company reputation). Special attention should be given those hazards that have operational consequences, since the support organization is responsible to retain the operability of the public transport system in case of an incident. This responsibility is shared with the other support organizations working with the public transport system, for example, the infrastructure support. Hence minimizing the operational consequences of a hazard requires cooperation between many support organizations, and initiatives should be taken to discuss and create common plans of actions.

7.8 Trade-off Analysis

All strategic decision making involves trade-offs. A decision that has positive effects on the maintenance organization may have negative effects on other parts of the organization, and vice versa. Maintenance managers, traffic planners, and other decision makers within the public transport organization, must therefore always take into consideration the total impact on the transit system.

For example, if the traffic planner increases the number of departures without expanding the train fleet, then fewer extra vehicles will be available when a vehicle breaks down and must be taken out of traffic. The increased number of departures will also result in less time available

The Support Organization: A Strategic and Value Adding Force

for maintenance, as well as an increased workload in the maintenance organization. Hence before the decision is made it must be considered whether:

- the passengers favor more departures or higher availability.
- the increased workload in the maintenance organization requires any investments.

The passengers' preferences should be known from survey studies. If the matter in question has not been studied in previous surveys, then it should be included in future surveys.

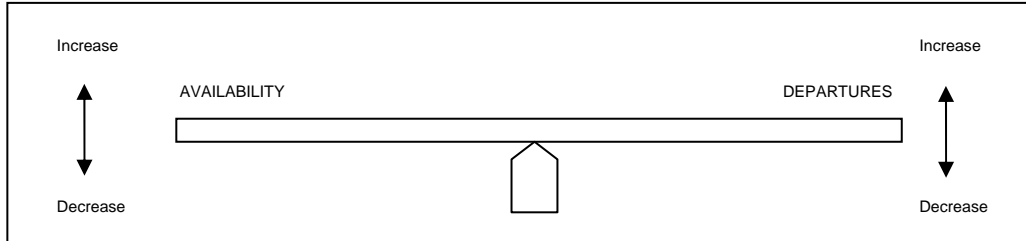


Figure 7-10: The trade-off model.

These situations arise frequently in a complex system and careful trade-off analysis must be performed in order to make sound strategic decisions.

7.9 Focused Maintenance

Focused manufacturing is a production management theory that stresses the advantage of being excellent at doing one thing, rather than being average at doing many things. This implies that a small production plant that is focused on one or a few products will, for those particular products, outperform a large production plant that manufactures a wide range of products. The problem in a production plant with a diverse product mix is that the properties of the products will place conflicting demands on the production process. In order to meet these demands, compromises must be made. This in turn will lead to a production process that is not optimal, and thus not competitive to that of a focused production plant⁽¹³⁾.

The advantages of being focused also apply to the maintenance case. Maintenance tasks, just like products, will place different demands on the maintenance organization. The maintenance focus will also depend on how the various maintenance activities influence the value drivers. Planning of preventive maintenance requires a cost control focus, while the handling of corrective maintenance requires an asset utilization focus.

The demands on the maintenance organization could, for example, concern resource requirements, and time to complete the tasks. Production managers usually have the option to drop products that are not suited for the production process. Maintenance managers do not have this option, since all maintenance tasks must be performed. The organization must therefore be designed to handle all maintenance tasks. The solution to this is to create sub-organizations, with a process oriented management, that are designed for a specific category of maintenance tasks. In the public transport case it is intuitive to divide the tasks into four categories with respect to the following properties: heavy or light maintenance, and corrective or preventive maintenance.

The Support Organization: A Strategic and Value Adding Force

Each sub-organization should be designed to fit the demands of the task category it is intended to support. Task profiling is a way to analyze the fit between the tasks and the maintenance organization. The tasks are evaluated against a number of relevant criteria regarding various aspects of the maintenance organization. A straight line connecting the dots indicates that it is possible to design a maintenance organization that fits well with the demands of that category (see figure 7-11).

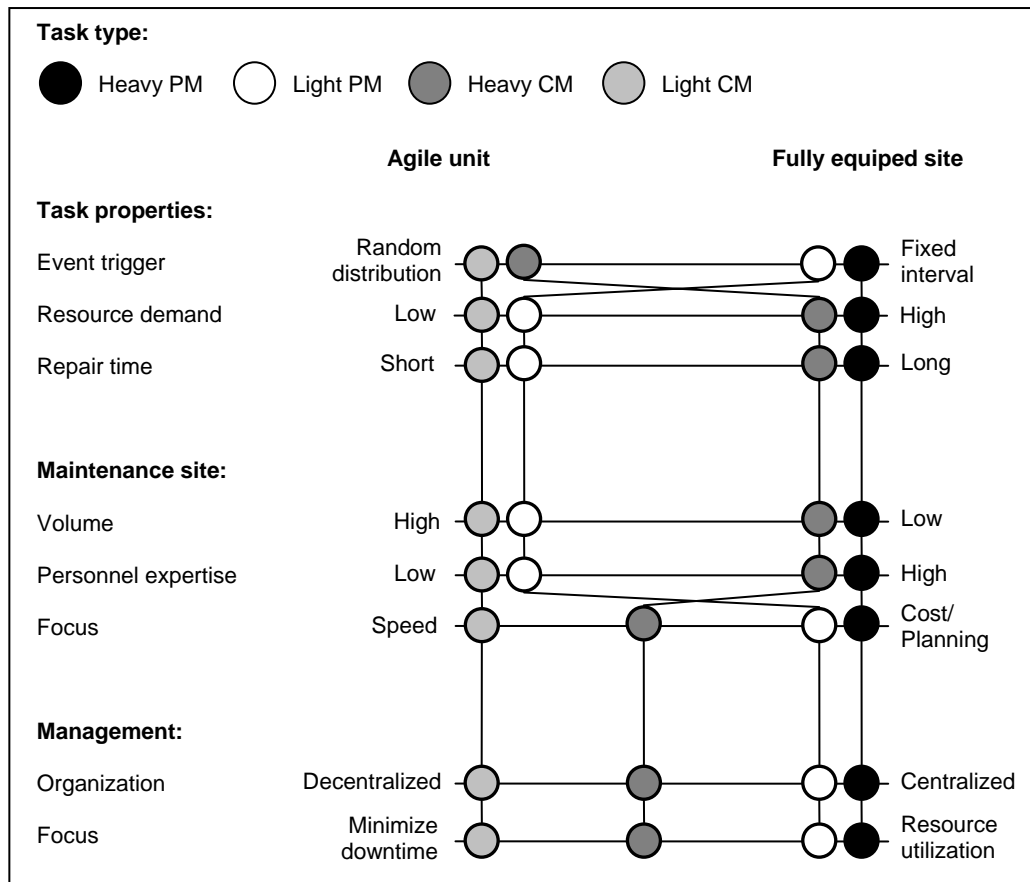


Figure 7-11: Task profiling of the suggested categories (developed from Hill, 2000).

The conclusion from the task profiling in this case is that three different maintenance sites would be needed to handle the shifting demands – one fully equipped depot, one small lightly equipped depot, and one agile support unit. In addition to this, redundancies should be introduced to reduce the need for unscheduled corrective maintenance, and the vehicle operators should be trained to handle some of the light CM and PM. Total Productive Maintenance (TPM) is a theory that emphasizes how the asset utilization can be improved drastically by training the operators to perform first-line maintenance. The TPM concept was originally developed in the late 1960s by Toyota in Japan, and it has since the 1980s been used

The Support Organization: A Strategic and Value Adding Force

with great success in many industries and countries. Haarman et al (2004) lists the following three preconditions that are necessary for a successful use of TPM⁽¹⁰⁾:

- direct contact between operator and machine
- willingness to change culture
- prolonged support and commitment by management

In the public transport case, TPM should be seen as a source of inspiration on how to extend the operators involvement in the maintenance work, rather than a panacea. All parts of the TPM concept may not perfectly apply to the public transport case, and the pros and cons of a complete implementation of TPM should thus be carefully considered.

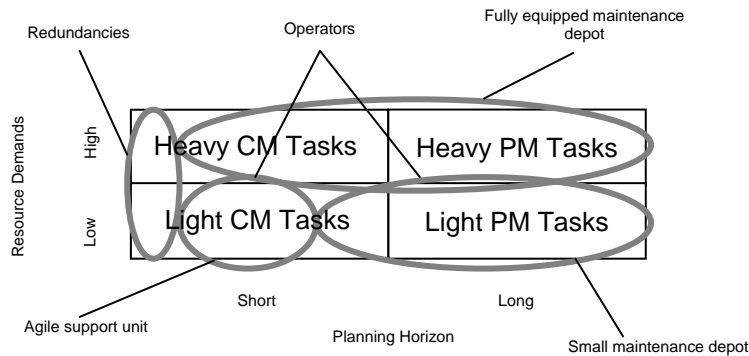


Figure 7-12: A focused maintenance solution.

With this focused maintenance solution, all heavy maintenance tasks are directed to one large depot. This depot should be fully equipped with spares, expertise personnel etc. The gathering of all important resources at one location allows for an optimized utilization. This depot should be complemented with a small depot designed to perform light preventive maintenance tasks. The main purpose of this site is to prevent expensive resources, such as expert technicians, from being tied up to light maintenance. The key focus of the small depot should be cost effectiveness. A third agile support unit should be responsible for the light corrective maintenance, and the insertion of replacement vehicles. This unit should be designed to quickly fix small problems on-site, for example malfunctioning doors etc. The focus of this unit should be agility and flexibility. Implementing a focused maintenance organization with these three separate sub-units will allow each unit to develop a maintenance strategy that best fits the demands of the tasks they are assigned.

7.10 Maintenance Outsourcing

Strategic decisions regarding maintenance outsourcing requires careful consideration. A basic guideline to outsourcing is that functions that are considered core activities of the organization and hence are of strategic competitive importance should be controlled in-house. If the

The Support Organization: A Strategic and Value Adding Force

maintenance function is considered a core activity then it is crucial that the function is competitive on the market, if not it should be re-engineered until it becomes competitive⁽⁸⁾.

	Strategic	Non-Strategic
Competitive	Keep Control	Needs Discussion
Non-Competitive	Re-engineer	Outsource

Figure 7-13: (Dunn, 2000)

With this viewpoint, the conclusion is that in the public transport case the maintenance function must be competitive and should be controlled in-house. However, in this case, there may not be a realistic possibility of becoming competitive against external maintenance contractors. This creates a dilemma on how to achieve an in-house controlled competitive maintenance function. The solution is partial outsourcing, where strategically important processes such as analysis, planning and follow-up are kept in-house, while work scheduling and work execution is outsourced to a maintenance contractor. The same goes for resources where facilities, strategic high cost components etc. are owned in-house, and personnel is provided by the contractor⁽⁸⁾.

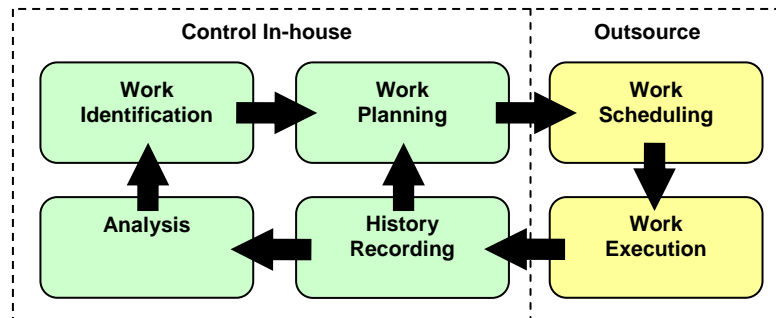


Figure 7-14: Partial outsourcing (Dunn, 2000)

Establishing an appropriate payment structure with this organizational set-up is complicated. The parties have to agree on suitable performance measures, and estimate the economic value of an increase or decrease of the measures. In this case, unavailability is likely to be a good measure. The maintenance contractor can however not be accountable for all incidents resulting in unavailability, thus it must be settled what is within the contractor's control.

Based on this the payment program should consist of a fixed charge for the minimum required availability, plus a reward system that is directly related to the economic affect the measure has on the company. Understanding the economic value of increased availability is crucial in order to design a payment program that optimizes the profit of both parties.

The Support Organization: A Strategic and Value Adding Force

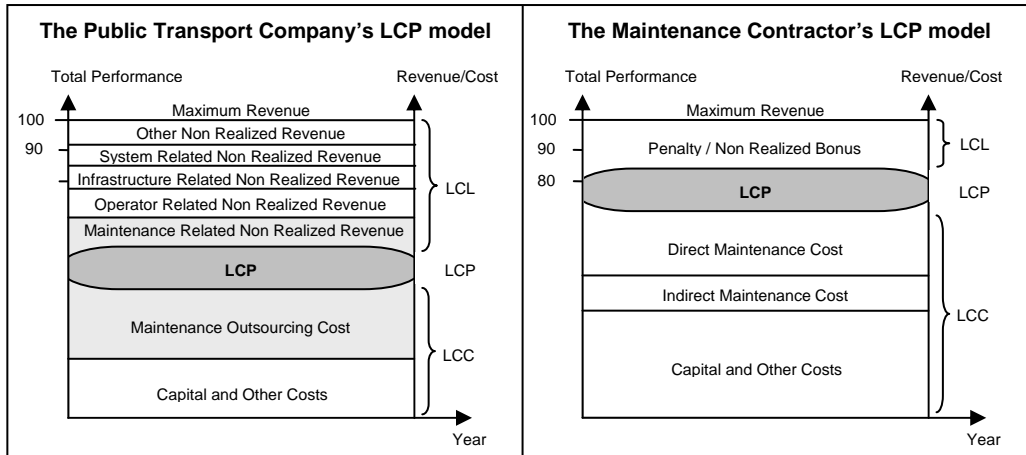


Figure 7-15: The payment program illustrated in the parties' LCP models. The light grey area highlights cost/profit elements of the public transport company that are included in the payment program.

The reward system could also be based on a mix of objective and subjective performance parameters. Customer Satisfaction Index (CSI) is one important subjective measure that may be included in the reward system. The objectives matrix (OMAX) approach is a straightforward method that combines target values for multiple indicators and weights them into a single performance index that, in turn, could be linked to the reward system. In the objective matrix each measure is entered on a scale from 0 to 10, where the 3rd level corresponds to the present parameter value and the 10th level shows the target value. The measures are then weighted based on importance. The performance index is calculated as the product of the score and the weight, and summarized over all measures⁽²²⁾.

Performance Measure				
MRUA	CSI	MWT	Q	
0.60%	91%	310 min	89%	Performance
0	100.0	30	100	10
0.1	97.5	40	98	9
0.05	95.0	60	95	8
0.15	92.5	80	90	7
0.20	90.0	100	85	6
0.30	85.0	120	80	5
0.40	80.0	180	75	4
0.50	75.0	240	70	3
1.00	50.0	300	50	2
2.00	30.0	420	30	1
3.00	20.0	540	20	0
3	6	2	7	Score
40	20	15	25	Weight (%)
120	120	30	175	Value
				Index 445

Figure 7-16: Objectives matrix with four performance measures: Maintenance Related Unavailability (MRUA), Customer Satisfaction Index (CSI), Mean Waiting Time (MWT), Quality (Q) (developed from Parsons, 2001).

7.11 Optimize Resources to Maximize Profit

In traditional LCC analysis, resources are optimized to minimize cost, and the original LCC formula is written as follows:

$$LCC = LAC + LSC + LOC + LDC$$

If the system has already been acquired, then the acquisition cost (LAC) and disposal cost (LDC) can be assumed to be fixed and independent of LSC and LOC. Hence in order to minimize LCC, the objective must be to reduce LSC and LOC. Consequently, LSC is the cost element of interest to the maintenance organization, and the optimal LSC value is determined from the lowest acceptable availability or the highest acceptable support cost.

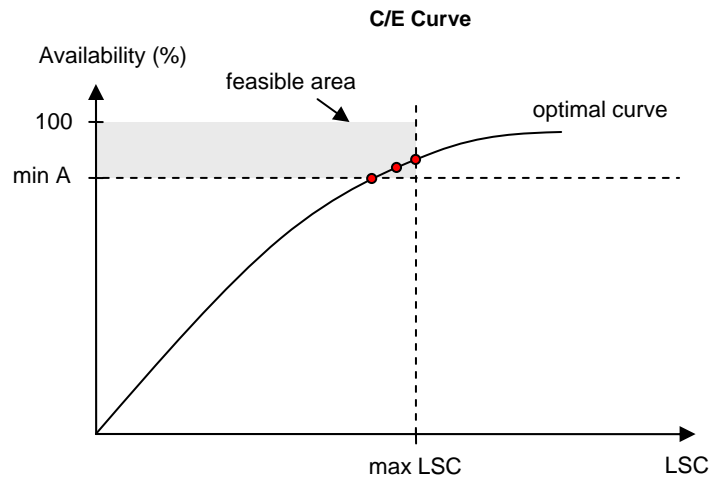


Figure 7-17: Cost/effectiveness curve.

However, this approach is not satisfactory for a revenue generating business, since it does not consider that LSC and Life Cycle Revenue (LCR) are dependent through the availability variable. To cover this, the analysis must be extended to a LCP perspective:

$$LCP(a) = LAC + LSC(a) + LOC(a) + LCR(a) + LDC$$

With this approach the objective is moved from minimizing the support cost to instead seek the optimal solution for the whole organization from a profit perspective. The extended analysis requires additional input parameters regarding revenue and operational cost, but this should not be a problem since the information most likely already exists within the organization. In the public transport case, revenue could be expressed as the income from ticket sales minus the cost of unavailability, which, for example, include replacement traffic (i.e. buses, taxis etc.). Cancelled departures will also violate the public trust, which could be very costly in the long term, but it is hard to estimate this cost.

It is crucial that all significant resource costs are included in the resource allocation analysis. A European benchmark study on maintenance expenditures shows that personnel costs account for the largest expenditure (47%) followed by material costs (27%) and cost of external services (20%) (source: EBSOM 1993)⁽¹¹⁾.

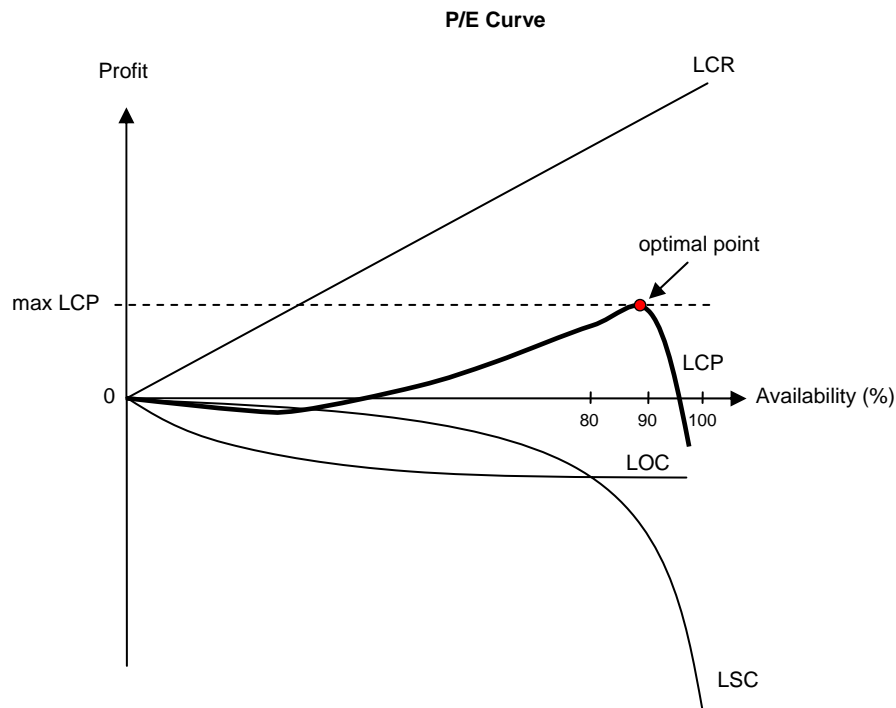


Figure 7-18: Profit/effectiveness curve.

7.12 Strategic and Profit Driven Incentive Program

The top management should develop and implement a performance incentive program that encourages all functions within the organization to move in the agreed direction. This program could include tangible targets such as economic performance, and achieved traffic volume, as well intangible targets like customer satisfaction. The performance should be measured from KPIs (Key Performance Indicators) that promote the desired outcome.

The identification of suitable KPIs is a complicated process that requires careful considerations. A systematic approach to this process is described by Hägerby et al (2002) and Parida (2006). They suggest a three level hierarchical breakdown of maintenance indicators. This maintenance KPI model is designed to be generally applicable, and the hierarchical levels are intended to adjust the KPIs according to the level in the organizational hierarchy^(12,21).

The Support Organization: A Strategic and Value Adding Force

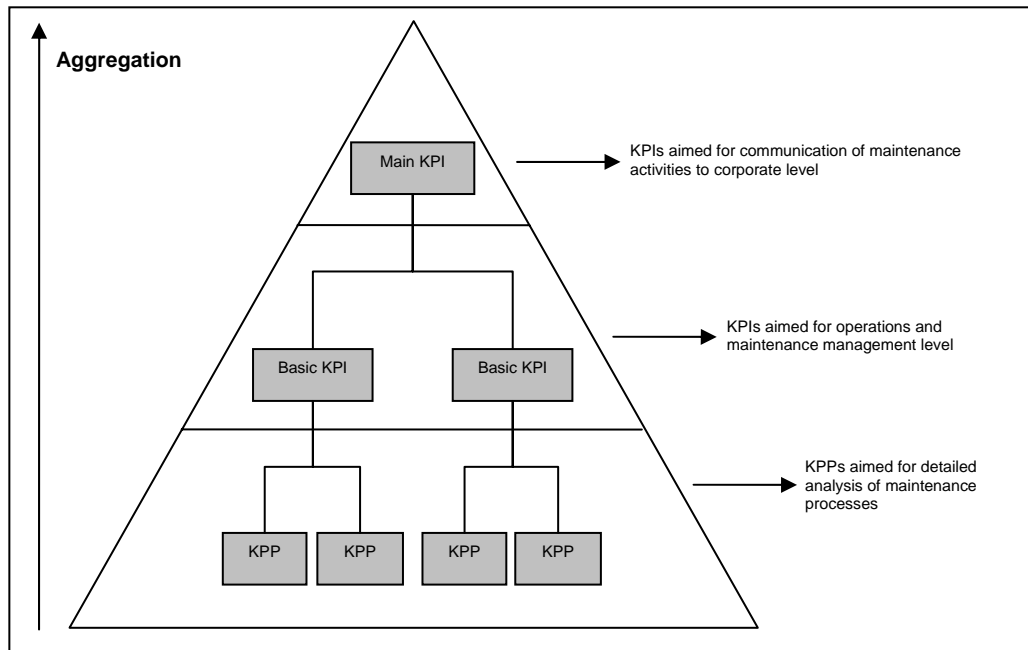


Figure 7-19: The maintenance KPI model, KPP=Key Performance Parameter (Hägerby et al, 2002).

The selection of appropriate KPIs and KPPs for the public transport case will depend on aspects such as the passenger's preferences, the revenue generating activities etc. The main KPIs that are intended for communication to the top management should directly reflect the goals of the organization, and preferably concern economic measures rather than technical measures. Typical goals of a public transport company could be to increase the number of people using public transport, make public transport affordable for everybody, increase the profitability etc. The balanced scorecard (BSC) model provides a framework that facilitates the translation of corporate goals into measurable indicators⁽¹⁾.

In this case, a relevant main KPI related to the maintenance organization would be the loss of income due to unavailability in relation to the total support cost. The basic KPIs will vary between the sub-organizations if focused maintenance is applied. In the suggested focused organization the basic KPI for the fully equipped maintenance site could be cost effectiveness, and for the agile support unit it could be availability and customer satisfaction. The KPPs are usually of more technical character such as, for example, mean downtime, mean time to insert replacement vehicle, resource utilization, and capital tied up in spares. The incentive of using the mentioned KPPs and KPIs would be that shorter downtime and quicker insertion of replacement vehicles lead to increased availability. More efficient resource utilization and reduction in capital tied up in spares mean higher cost effectiveness. Higher availability will increase the revenue, and higher cost effectiveness will decrease the total support cost. A lower support cost allows for lower fares without affecting the profit margin. Higher availability and lower fares should attract more passengers and hence increase the profitability. This example

The Support Organization: A Strategic and Value Adding Force

demonstrates that focusing on the key tasks at every level in the organization will eventually result in the realization of the corporate objectives.

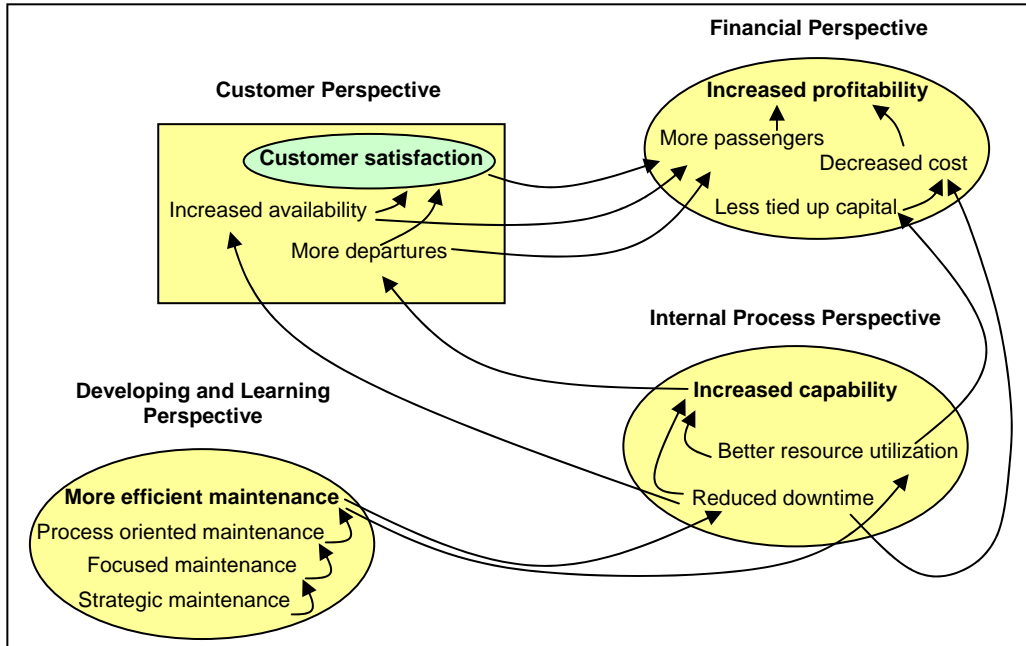


Figure 7-20: Balanced scorecard illustrating the cause effect interrelation in a public transport system (developed from Ahlmann, 2002).

A central part of an incentive program is to set targets for all performance indicators. Setting these targets requires much experience and consideration. The VDM concept emphasizes benchmarking against organizations in the same industry as the primary tool for setting up targets and evaluating the maintenance organizations performance. The difficulty with benchmarking is to find organizations that use the same performance indicators, and even if that is found there is still uncertainty whether they measure the indicator in the exact same way. To overcome this obstacle the founders of the VDM concept have developed the on-line VDM Control Panel. The idea with the VDM Control Panel is that organizations that agree to share their maintenance data, will receive access to other participating organizations' data. The VDM Control Panel includes 10 predefined KPIs that all participating organizations must measure, and clear specifications of the data that must be gathered. A complete list of the 10 KPIs used for the VDM Control Panel is found in Appendix II. Apart from benchmarking, past performance data and future prognosis are two other useful inputs when setting suitable KPI targets⁽¹⁰⁾.

7.13 Continuous Improvements

The acceptance of an ever changing environment is fundamental to all strategic thinking. This means that the best strategic solution today may not be the best strategic solution next year or five years from today. Hence, strategic maintenance organizations should always be open minded towards improvements and reconsiderations of the current practices.

Western management philosophies are typically result oriented, and stress the importance of control, performance, results, and financial rewards. The following quote by management writer Peter Drucker perfectly captures this⁽²²⁾:

“Without productivity objectives, a business does not have direction. Without productivity measurement, a business does not have control

The use of performance incentive programs, reward systems etc. originates from the western management philosophies.

Japanese management philosophies however, represent a completely different thinking of successful management, which stresses a process oriented approach. The process oriented management, which is also people oriented, focuses on development, commitment, and communication. The Japanese management philosophy *Kaizen*, which means “change to the better”, embraces the process oriented and continuous improvement approach, and involves everyone in the organization from the top management to the workers. *Kaizen* is not one theory, but an attitude to always strive for improvements in every part of life, at home, at work etc. It is simply a way of life. Japan’s tremendous industrial development over the last 50 years is clearly related to *Kaizen*⁽¹⁶⁾.

Although productivity objectives and productivity measures are important in order to direct and control the business, they do not by themselves provide the means necessary to achieve the proposed transition into a strategic and value driven support organization. Hence, *Kaizen* mentality must be part of this transition process. Central to organizations driven by *Kaizen* philosophy is customer satisfaction. The purpose of the organization is to always satisfy and serve the customers’ needs, and all improvements should in the end benefit the customer. *Kaizen* particularly emphasizes everybody’s involvement and the gradual everyday improvements such as, for example, a worker finding a more efficient way of performing a task, or a maintenance technician finding a way to increase the equipment’s reliability etc. *Kaizen* is not about the abrupt large improvements caused by, for example, investments in new modern production facilities. The strength of Japanese management lies in its success in developing and implementing systems that acknowledge the objectives, but still emphasize the means⁽¹⁶⁾.

Kaizen is often illustrated as an umbrella covering various concepts designed to promote *Kaizen* thinking, for example TPM, the PDSA cycle, customer orientation just to mention a few. Which of these concepts that should be applied to the public transport maintenance organization may depend, but what is crucial is that the management is aware of and promotes *Kaizen* to everyone in the organization including external suppliers⁽¹⁶⁾.

8 Implementing Strategic and Value Driven Concepts in the ILS Toolbox

The complexity of public transport systems and the vast amount of input data make it highly impractical to carry out analytical studies without the aid of computers. Systecon provides a complete suite of computer software tools (the ILS toolbox) that enables these studies, including:

- *Bal* – tool designed to analyze the preventive maintenance distribution over time, and to package preventive maintenance tasks into suitable groups.
- *Opus10* – advanced spare part optimization tool.
- *Simlox* – tool for modeling and simulation of complex systems.
- *Catloc* – LCC analysis tool that links maintenance data to financial data.
- *Madcat* – tool providing statistical methods to analyze and verify the reliability development over time.

This chapter presents a systematic approach on how to integrate results from the various tools in order to facilitate the development of a strategic and value driven support organization. It also describes the application of the tools in the public transport case, and evaluates the need for extended functionality in the tools.

Madcat is only described briefly, since Madcat's main area of use does not concern the development of the support organization.

8.1 Systematic Integration of the ILS Tools

The systematic integration of the ILS tools starts with the analysis of RAM data in *Bal* and *Opus10*. Preventive maintenance is categorized and packaged in *Bal*, and stock levels are optimized in *Opus10*. The preventive maintenance packages and stock levels are then exported to *Simlox*.

The *Simlox* model is completed with additional resources and operational data before the simulation is carried out. Key results from the simulation are operational availability, resource utilization, and number of backorders per item. *Simlox* does not have the functionality to model financial data. The *Simlox* model along with the simulation output must thus be exported to *Catloc*, where cost and revenue items can be linked to the simulation model. *Catloc* also provides the possibility to perform sensitivity analyses in order to identify significant value drivers.

This chain of analytical and simulation studies produces all the significant information required for the decision making, i.e. operational availability, optimal stock levels, preventive maintenance packages, and an LCP model that can be used both to analyze the profitability and to identify value drivers. One of the major strengths of computer modeling is the opportunity to inexpensively test multiple configurations until satisfying results are obtained. For example, the simulation study may show that the packaging solution is not compatible with the operational

profile, or the value driver analysis along with the simulated resource utilization may indicate that there is an overcapacity of a specific resource that reduces the profitability.

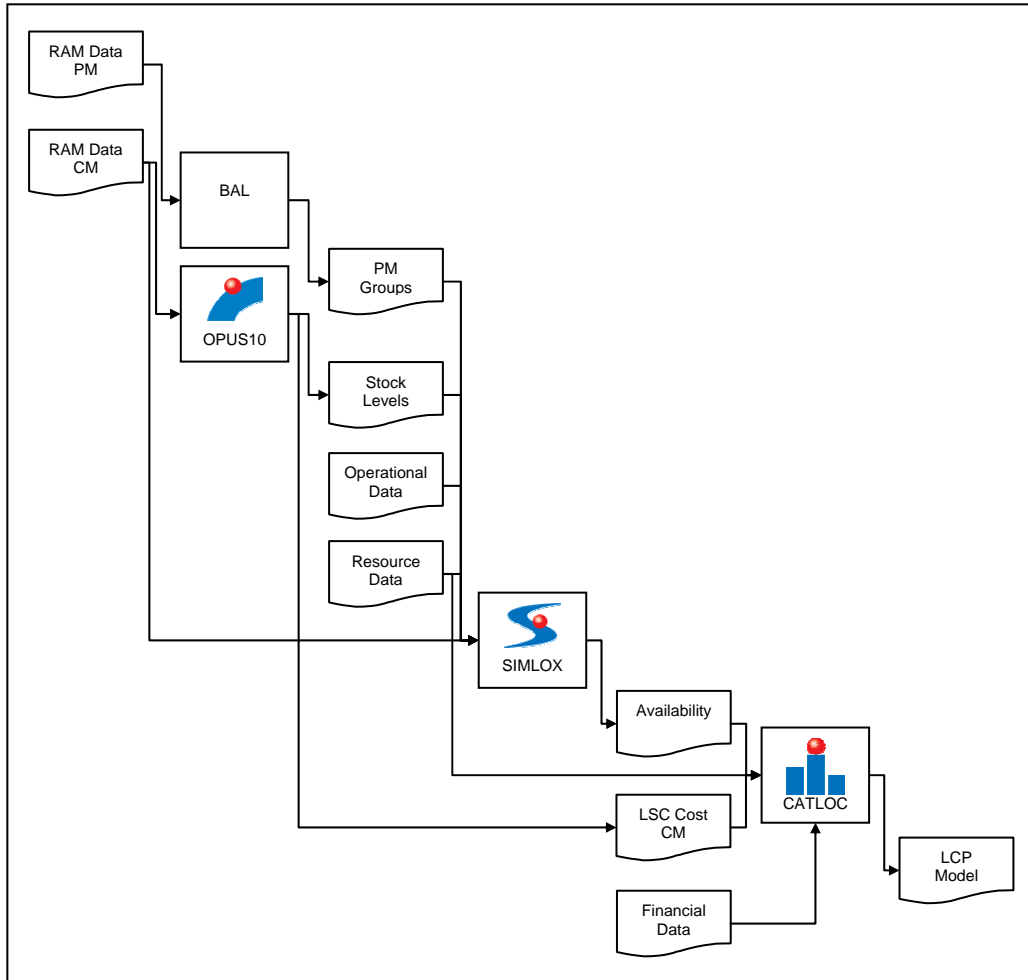


Figure 8-1: Systematic integration of analytical and simulation results.

The most central part of the described approach is the integration of Opus10 and Simlox results in Catloc. Today Opus10 and Simlox are used to analyze specific issues that arise during the development of the maintenance organization, but these results are not related to the larger context. This makes it difficult for the decision maker to obtain a complete picture of the situation and to understand how these solutions influence the overall performance and profitability. Hence there is a need to link these results to the financial figures, and Catloc has all the necessary functionalities to accomplish this.

The Support Organization: A Strategic and Value Adding Force

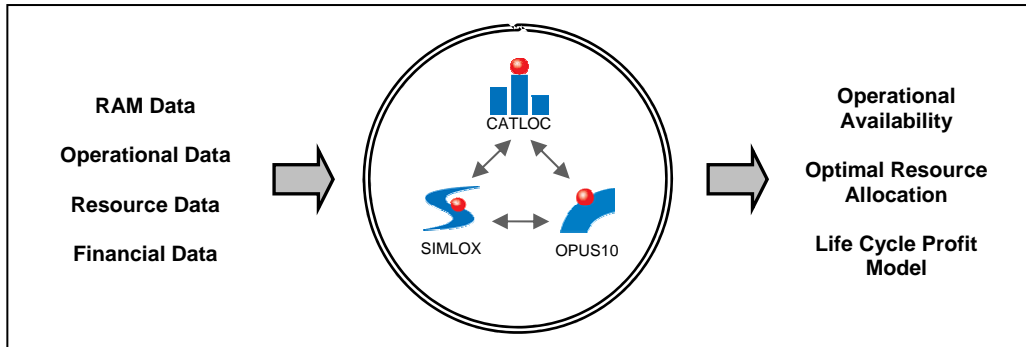


Figure 8-2: Integrating Opus10 and Simlox with Catloc.

8.2 Bal: Preventive Maintenance Analysis and Packaging

In the public transport case, Bal has been used in the early stages of the project to gain a deeper understanding of the magnitude of the maintenance workload over the vehicles' whole life cycle. The purpose of a Bal analysis is to study where in time the major preventive maintenance tasks will occur and how they should be managed. The analysis is based on the preventive maintenance intervals and the delivery plan for the vehicles.

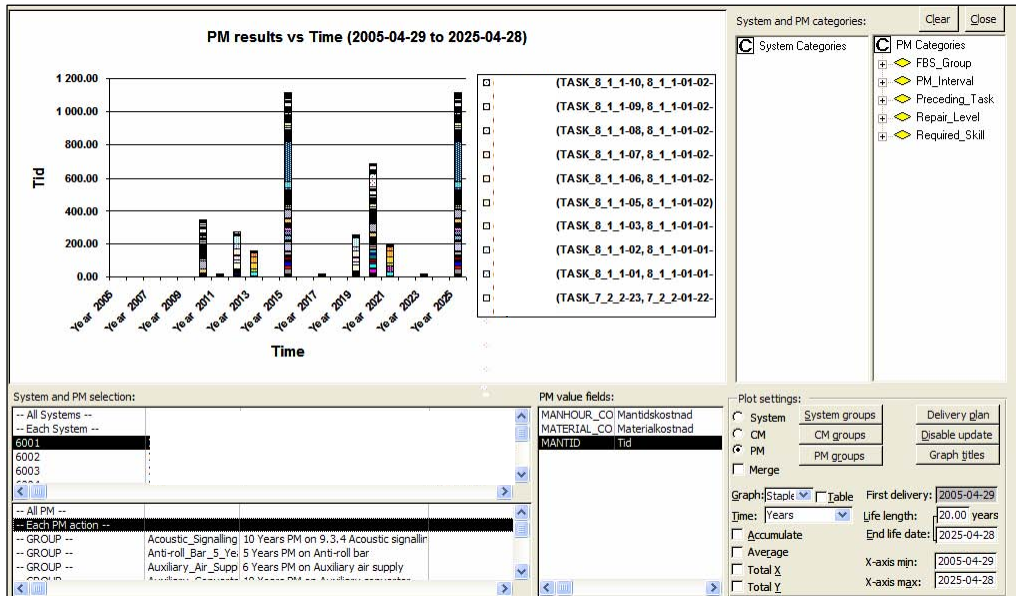


Figure 8-3: The distribution of preventive maintenance tasks over time displayed in Bal.

Bal also offers a packaging function that facilitates the packaging of preventive maintenance tasks. The function allows the user filter to data by various categories, such as task duration,

The Support Organization: A Strategic and Value Adding Force

PM interval, the component's function or location on the vehicle etc, and then create suitable packages of the filtered data. The packaging solution influences the operational availability significantly, since the packages must fit in with the operational profile. If the packages are too large, i.e. requiring long depot times, it may be impossible to uphold the balanced maintenance strategy, and with that follows resulting disturbances of the operation. The packages created in Bal are thus analyzed in Simlox to ensure that the packages are compatible with operational profile, and to study the resulting operational availability.

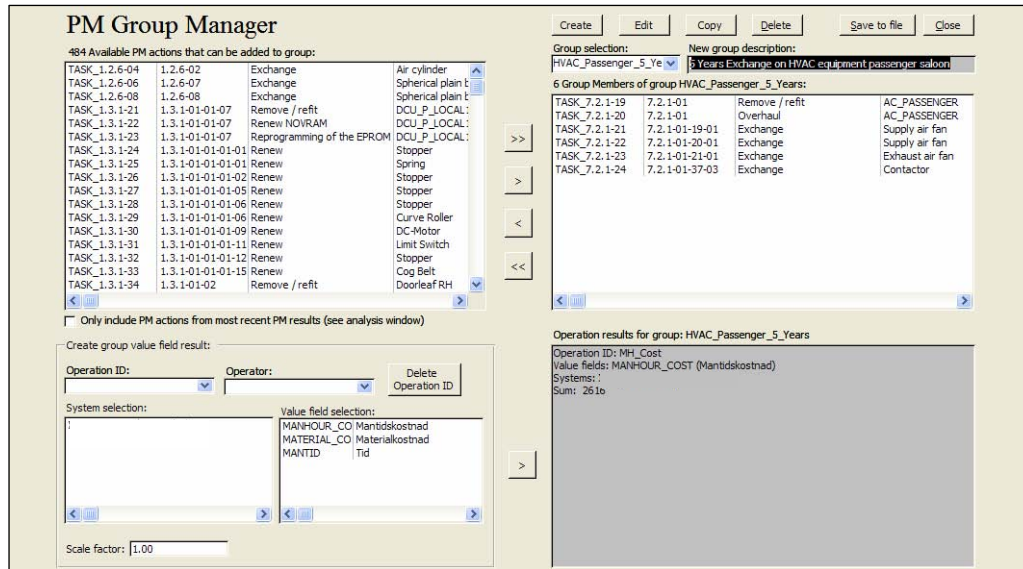


Figure 8-4: The PM Group Manager in Bal.

The packages in Bal currently have to be manually inserted in the Simlox model. Hence implementing an export function in Bal that arranges the packaging information in Simlox format would greatly facilitate the integration between Bal and Simlox. Another potential improvement area in Bal is the item structure. Bal only supports a flat item structure, while Simlox as well as Opus10 and Catloc support an unrestricted tree structure. This modeling limitation in Bal restrains the possibility to build system structures identical to those in the other tools.

8.3 Opus10: Calculate Optimal Stock Levels and Corrective Maintenance Cost

Opus10 is an optimization tool that calculates optimal stock levels and the corresponding life support cost. The result is presented in a cost/effectiveness graph where availability is plotted against the support cost. Every point on the graph holds the optimal allocation of spares for that specific availability and cost. The availability measure in Opus10 should not be confused with the operational availability, but rather seen as the availability of spares. How a certain degree of availability in Opus10 relates to the actual operational availability depends on many factors

such as, for example, reliability of the system, availability of maintenance personnel, and availability of repair tracks and tools. So in order to analyze the total effect of an Opus10 solution, it must be integrated with Simlox that, in turn, allows for more complete modeling of the support organization. The process of calculating optimal stock levels in Opus10 and evaluating them in Simlox should be repeated until the operational and financial results are satisfying.

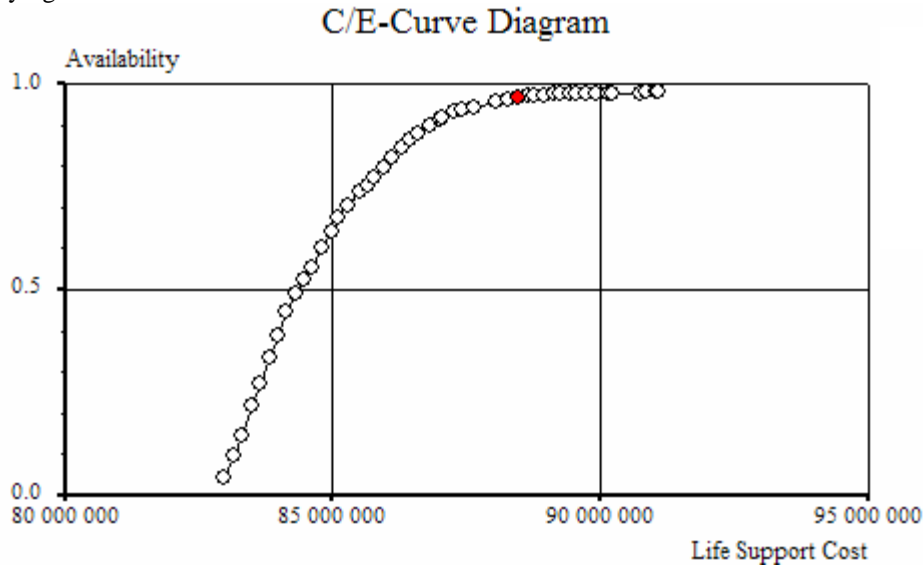


Figure 8-5: Cost/effectiveness curve in Opus10.

The optimization method Opus10 uses relies on proven mathematical theories to calculate the optimal stock levels. This means that the results are guaranteed to be one hundred percent optimal for that specific model. Another benefit with the mathematical approach, compared to simulation, is the fast execution times. However, analytical models are less flexible than simulation models, since implementing new functionalities requires solid mathematical backup. A drawback with lower flexibility in the modeling process is that it may lead to more assumptions. It is for example in the current Opus10 release not possible to divide up maintenance tasks of the same vehicle between two or more depots, and it is not possible to model operational profiles. Statistician John Tukey hits the nail on the head in the following quote⁽⁷⁾:

"An approximate answer to the right problem is worth a good deal more than an exact answer to an approximate problem"

The rapid development of computer technology has resulted in that simulation techniques now can handle more and more complex problems with acceptable execution times. There are spare allocation tools on the market today that build on simulation technique, which brings increased modeling flexibility. These simulation "optimization" tools may become serious competitors to analytical optimization tools. Thus it is important to evaluate the pros and cons with the current analytical approach in Opus10 in order not to jeopardize the tool's future competitiveness.

8.4 *Simlox: Simulate Operational Availability and Resource Utilization*

Simulation is doubtless the most important decision support tool for complex systems. The technique is extremely versatile, which makes it usable for almost any type of analysis and system. Although analytical methods have many advantages to simulation, they can only be used for limited parts of the analysis of a complex system, since it is not always practical or possible to construct analytical models. Hence large parts of the support analysis rely on simulation results.

Due to the importance of simulation in the public transport case, this thesis includes a detailed evaluation of the functionality of Simlox. The evaluation was carried out as a comparison study between Simlox and a reference simulation tool – Simul8. Simlox is a closed loop discrete event simulation tool. In a closed loop simulation all systems are defined at the beginning of the simulation and will then follow a cycle of states throughout the simulation period. The cycle includes the following states: on mission, waiting for maintenance, active repair, and ready for mission. Simul8 is an input-output simulation tool that is generally used to simulate a flow, for example the production flow in a factory, or as in this case the flow of maintenance activities at a depot.

The case chosen for the comparison study was a repair track analysis, where the various repair track solutions were simulated in order to find the optimal balance between resource utilization and operational availability. The Simlox model and output is found in Appendix III, and the Simul8 model and output is found in Appendix IV.

The conclusion from the evaluation is that the interface in Simlox is excellent for setting up complex systems and timetables. Simlox also gives the possibility to simulate vehicles as individual systems, which has great advantages. This makes it possible to assign any mathematical distribution for the failure rate, and it also allows for more detailed rules on how non critical errors should be handled. In addition to this, Simlox offers a large selection of predefined result views. These views provide the basic information required for the decision making process. The fast execution time in Simlox also makes it possible to run multiple simulations and gain statistical confidence of the results.

One area where Simlox has a potential for improvements is the modeling of the support organization. The major drawback with the current solution is that it is not intuitive, and not flexible enough. For example, it is not possible to redirect the vehicles between the depots based on the maintenance task, which is required when simulating a focused maintenance organization. One way to improve this would be to implement a modeling interface for the support organization that handles an in and out flow of maintenance tasks. The idea is to use the current Simlox interface to model the systems and operational profiles. Systems that require maintenance will enter the support organization, which is modeled as a production flow. This allows for unlimited flexibility in the modeling of complex support scenarios. With this solution, it would be possible to redirect maintenance work to different sites depending on the task type, required resources, the vehicle's location etc.

Another valuable improvement to Simlox would be to add the option to include financial data in the simulation model. This could, for example, concern the man-hour cost of the maintenance

staff or the cost of repair tracks. The vehicles also generate revenue when they are on mission, and a way to model this would be to add an income per successful mission hour, and a cost of mission failure.

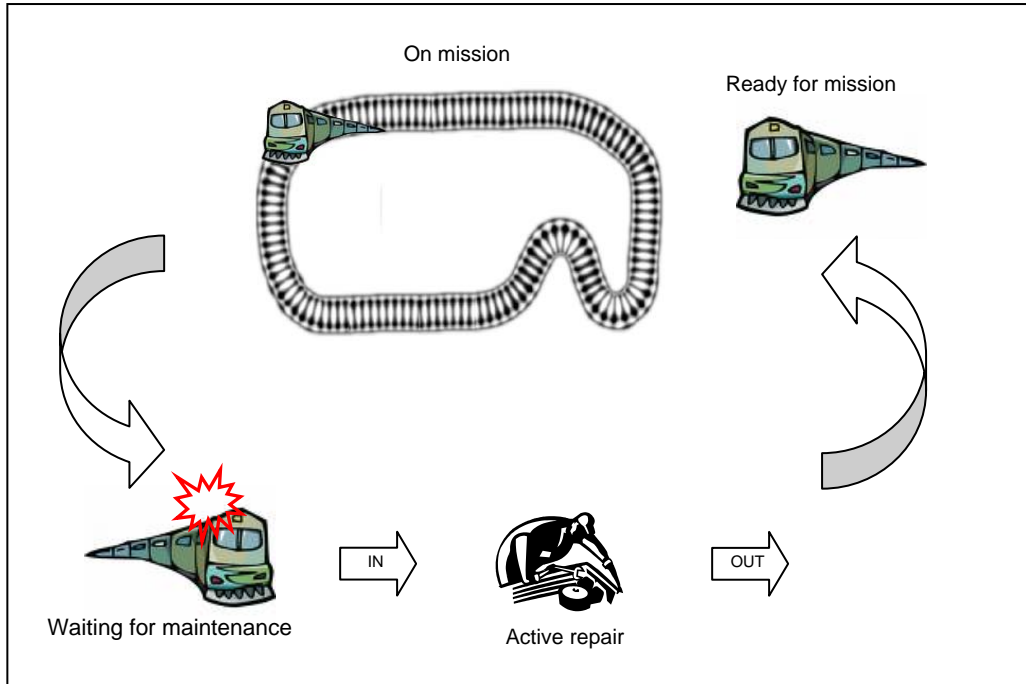


Figure 8-6: The mission cycle in Simlox.

8.5 Catloc: Compile the LCP Model and Identify Value Drives

In order to create the complete financial picture of all the analyses performed in Bal, Opus10, and Simlox, it is necessary to link the results to financial figures and compile it in one LCP model. This can effectively be achieved in Catloc.

Catloc is originally developed as an LCC analysis tool, but the flexible modeling interface also enables an LCP approach. However Catloc assumes an LCC model, so graphs titles etc. may be wrong and misleading in an LCP model, but as long as the modeler is aware of this, Catloc works perfectly fine as an LCP analysis tool.

The important cost/revenue elements to include in the LCP analysis when developing the public transport support organization are: investment costs in equipment and spares, corrective and preventive maintenance costs, delay costs, revenues from single trip tickets and monthly passes. The delay cost can be divided up in short-term delay costs and long-term delay costs. Long-term delay costs are often difficult to estimate since they concern subjective measures such as company recognition and brand name etc. To begin with, it is therefore recommended to start

The Support Organization: A Strategic and Value Adding Force

looking at short-term delay costs, which usually are more tangible like, for example, penalty fees due to delays and cancelled departures.

LCP (Life Cycle Profit)
LCC (Life Cycle Cost)
LAC (Life Acquisition Cost)
INV (Investment costs)
- Equipment and material purchase cost
- Engineering cost
- Installation cost
- Initial spares cost
- Initial training cost
LSC (Life Support Costs)
AMC (Annual maintenance costs)
- Corrective Maintenance cost
- Calendar based PM cost
- Condition based PM cost
LOC (Life Operating Cost)
AOC (Annual operating costs)
- Operating cost
- Energy consumption cost
ADC (Annual delay-time costs)
- Short-term delay cost
- Long-term delay cost
AHC (Annual hazard costs)
- Human safety cost
- Environmental threat cost
- Cleaning cost
- Rebuilding cost
LDC (Life Disposal Costs)
- Disposal and reinvestment cost
LCR (Life Cycle Revenue)
LSR (Life Sales Revenue)
ASR (Annual sales revenue)
- Revenue from Single Trip Tickets
- Revenue from Monthly Passes

Figure 8-7: Cost/revenue elements central to the Catloc analysis highlighted in grey.

A key strength in Catloc is the sensitivity analysis function. It could be used both to identify value drivers and to optimize all resources to maximize profitability. When doing the latter, the operational availability must be defined as a function of the costs and revenues it influences. Intuitively higher operational availability is on one hand associated with increased support costs, but on the other hand it generates more revenue, and vice versa. Thus the objective of the optimization is to find the optimal operational availability in order to maximize the profitability. This is achieved with a sensitivity analysis that calculates the total LCP over a range of availability values and plots it in a graph (see figure 8-9).

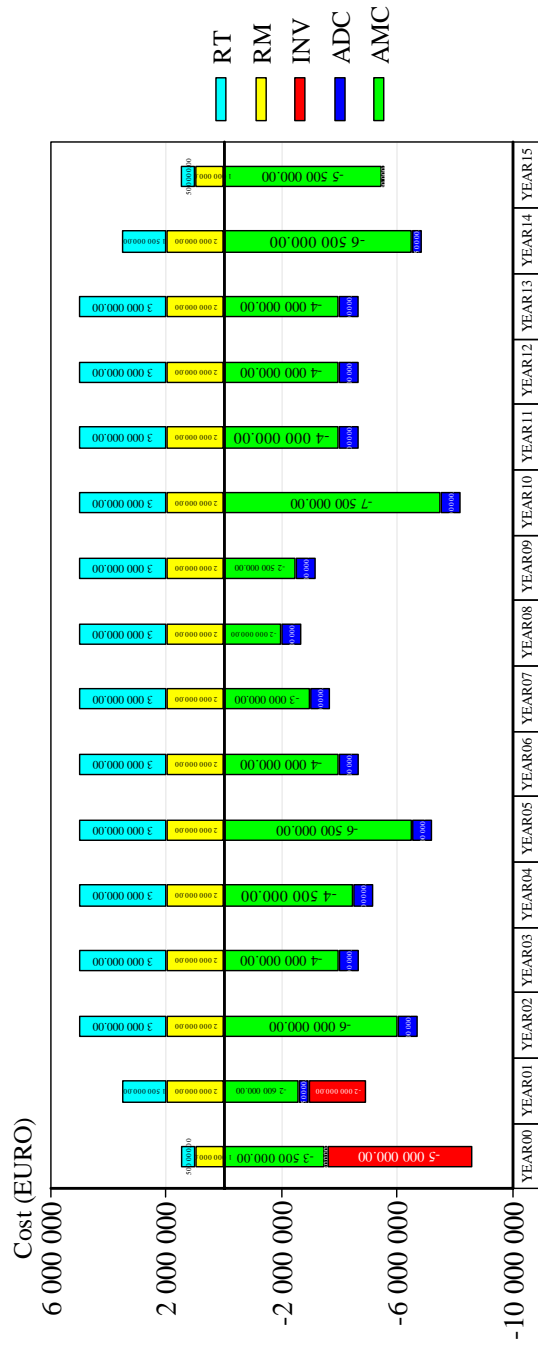


Figure 8-8: LCP model in Catloc

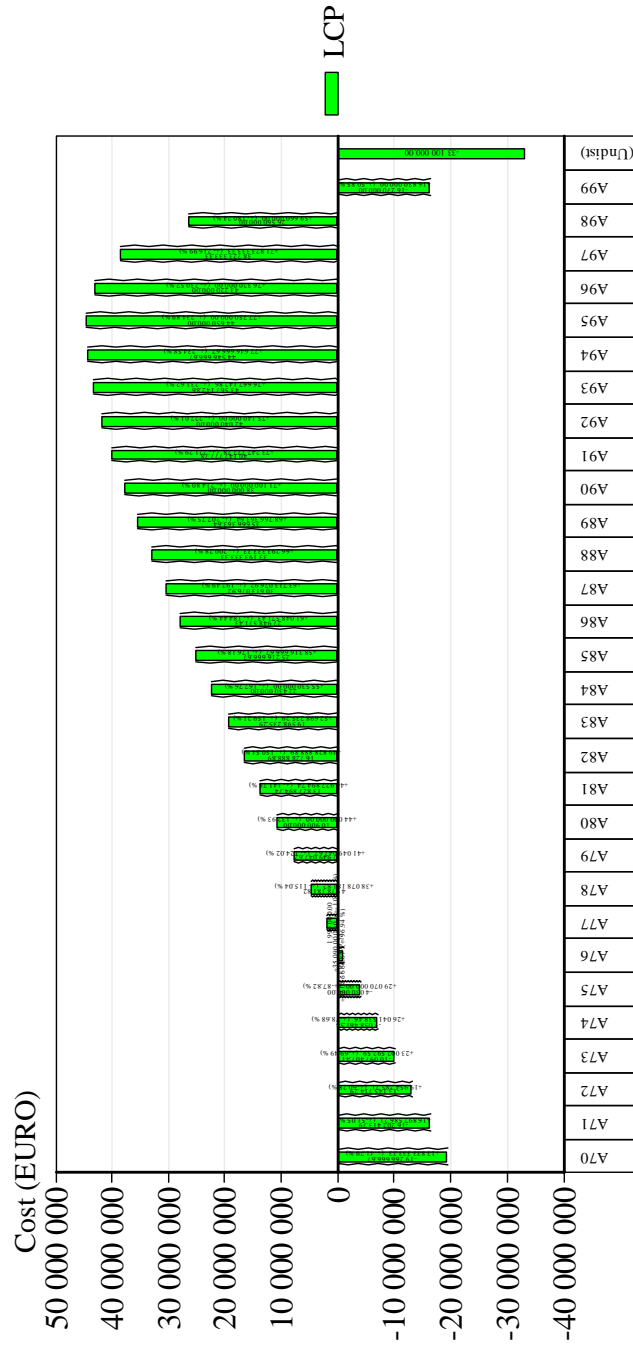


Figure 8-9: Sensitivity analysis of availability in Catloc

Catloc is to a large extent ready to be used as described in this section. However, the sensitivity function has to be modeled with a special solution and Opus10 data is automatically imported as positive values. The notation should also be adjusted to fit both LCC and LCP modeling. There are no obstacles to implementing these three improvements, and it would require little effort.

8.6 Madcat: Follow-up Analysis and Verification

Systecon's maintenance data analysis tool Madcat is used to make continuous follow-up analysis of the vehicle's performance. This includes trend and consequence analysis, as well as verification of reliability.

The analysis is done on different levels of detail in order to get a complete assessment of the system's condition. The trend analysis of the overall failure rate is used to verify that the vehicle is meeting the required reliability. This analysis can be further detailed by differentiating between stopping faults and non stopping faults. Trend analyses are also used to identify running-in periods, and to verify that design improvements are yielding desired results.

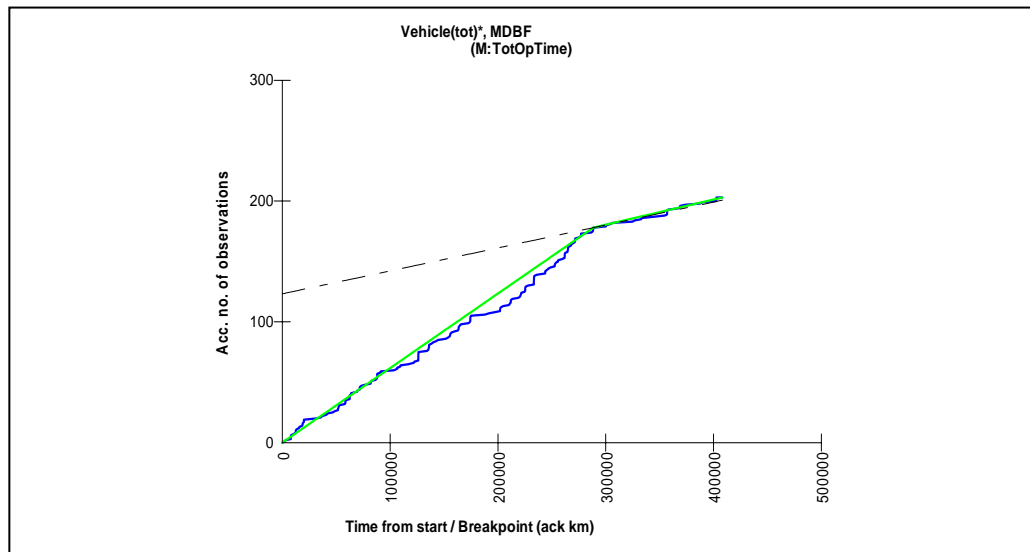


Figure 8-10: Example of trend analysis of overall failure rate (MDBF=Mean Distance Between Failure).

Histograms are used in subsequent more detailed analyses in order to, for example, identify the subsystems that account for most failures. This gives a good indication of where more careful analyses are necessary.

Histograms are also used to compare each component's present failure rate with its target value. A large divergence between present and target values could indicate that the vehicle may no longer meet the safety requirements.

9 Findings and Recommendations

9.1 Findings

The purpose of this master's thesis was to: analyze the support situation for rail transit vehicles, present a solution for how the development of a maintenance organization should be performed, and to evaluate and describe how Systecon's software suite should be integrated as a decision support tool in this process, and identify necessary improvements to the software.

The analysis of the support situation for rail transit vehicles leads to the conclusion that the vehicles possess some very central properties that were unnoticed in the current development of a maintenance strategy. Namely, that the vehicles generate revenue when they are operating and that the maintenance organization has great influence on the customer satisfaction and the achievement of the overall organizational strategy. The economic loss due to operational unavailability is actually double in the public transport case, since it results in both non-realized revenue and penalty fees for delays and cancelled departures. The current approach relies on theories that are suited for military systems such as, for example, LCC and ILS. The rail transit vehicles just like military systems are very complex and have a long lifetime, which means that operational costs and maintenance costs usually exceed the acquisition cost over the systems' lifetime. The LCC and ILS concepts are well suited for these types of problems, but they do not consider a strategic and revenue perspective. Hence, the theories must be completed with theories that do have this perspective.

Two modern maintenance theories that help to add the revenue perspective are the life cycle profit and the value driven maintenance concept. In addition, it has been found that the public transport maintenance organization has lots of similarities to a production company, and that production management theories thus could be used in the development of a maintenance strategy.

Based on the original LCC and ILS approach along with the LCP, VDM and manufacturing strategy perspective, a framework has been designed to facilitate the development of a strategic and value driven maintenance organization. The framework describes a cycle of activities that promotes a stronger focus on strategy and value. The beginning of the cycle concerns the importance of integrating the maintenance organization with the overall organizational strategy, and how the value drives and the passengers' preferences are central input to the development of a maintenance strategy. Once the maintenance strategy is defined, the maintenance management should analyze how the maintenance organization should be set up in order to achieve the maintenance strategy. The thesis identifies a set of concepts that are crucial in this process. This includes robustness, adaptability and risk analysis, as well as an evaluation of the maintenance requirements and if focused maintenance or outsourcing is preferred. Once it is decided how the maintenance organization should be formed, it is necessary to create a performance incentive program. This involves identifying key performance areas and finding suitable key performance indicators. Target values must then be assigned to the KPIs. The assessment of target values could be based on benchmarking with companies in the same industry, or historical data, or future expectations.

The implementation of the framework presented in this thesis will require much commitment from the entire organization. It will take time to change the deep rooted cost oriented thinking, and the performance incentive based management is not sufficient in order to achieve this cultural transition. Awareness throughout the organization and continuous gradual improvements are thus central for the realization of the ideas presented in the framework. The Japanese management philosophy Kaizen emphasizes the continuous improvement thinking and the importance of everyone's commitment in the transition process.

Systecon's software suite has proven to have most of the necessary functionalities required to facilitate the development of a strategic and value driven support organization. But used separately the tools do not have the functionalities to deliver the key decision support information such as a complete LCP model, value drivers, and optimized resource allocation in order to maximize profitability. Hence, what must be improved is the integrated use of the tools. The integration would be greatly enhanced if the tools had a shared modeling platform.

9.2 Recommendations

In these types of projects, Systecon engagement is usually limited to study specific issues. This makes it difficult to completely implement the framework presented in this thesis. However, some of the concepts are so central that they should under no circumstances be ignored. This regards the strategy and value concepts. Systecon should always strive to understand how the revenue side of the organization is related to the operational availability, and how the maintenance organization supports the overall business concept. If the client does not recognize maintenance as a value adding force, Systecon should attempt to convince the client to think in these terms, since it is obvious that every revenue generating business strives for higher profitability and not higher cost effectiveness. Higher cost effectiveness is only one possible way of achieving higher profitability. The value driver/value killer example (see section 7.3) perfectly illustrates this. In the same way, if the client does not recognize maintenance as a strategic force, Systecon should convince the client about this. In this case, the relationship between operational availability and customer satisfaction is usually very clear, and increased customer satisfaction is usually one of the key objectives in the corporate mission.

The thesis has also identified improvement areas in Systecon's software suite. In the short term Systecon is recommended to implement functionalities in the tools that handle revenue data, and to improve the import/export functions between the tools in order to smooth the integration. The modeling flexibility of the tools should also be enhanced. This includes better modeling interface for the modeling of maintenance organizations in Simlox, and an open mindedness towards the pros and cons of the analytical optimization approach compared to "optimization" through simulation. A recommendation for the long-term development of the software is to design a shared modeling platform between Opus10, Simlox, and Catloc.

9.3 For Future Research

The framework described in this thesis presents a new approach to how a public transport maintenance organization should be developed, which opens up more interesting research areas. This includes a study on the implementation of the framework in a real-life case.

Some concepts have only been mentioned briefly in the case and could be explored further. Two examples of such areas are the important process of understanding the passengers' preferences, and the process of creating a Kaizen culture in a western maintenance organization.

The ambition has been to make the framework as general as possible, thus it would be interesting to apply the framework to maintenance of other types of systems with similar characteristics. For example, the shipping industry that involves complex systems (i.e. the vessels) that generate revenue when they are on mission.

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Appendix I – SINTEF Cost Breakdown Structure

REMAIN (Railway maintenance) project by SINTEF (The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology) (1998)

1. INV (Investment costs of the system or equipment/product: primary investment)
 - 1.1 Equipment and material purchase cost
 - 1.2 Engineering cost
 - 1.3 Installation cost
 - 1.4 Initial spares cost
 - 1.5 Initial training cost
 - 1.6 Disposal and reinvestment cost
2. AMC (Annual maintenance and operating costs)
 - 2.1 Corrective Maintenance cost
 - 2.2 Calendar based PM cost
 - 2.3 Condition based PM cost
 - 2.4 Operating cost
 - 2.5 Energy consumption cost
3. ADC (Annual delay-time costs)
 - 3.1 Short term delay cost
 - 3.2 Long term delay cost
4. AHC (Annual hazard costs)
 - 4.1 Human safety cost
 - 4.2 Environmental threat cost
 - 4.3 Cleaning cost
 - 4.4 Rebuilding cost

Appendix II – The 10 KPIs Used in the VDM Control Panel

KPI	Definition
1. Maintenance costs / asset replacement value	Total maintenance cost divided by the replacement value of the production facility (equipment and equipment-related buildings).
2. Technical availability	Total available time for production minus the downtime caused by maintenance divided by the total available time for production (all measured per annum).
3. SHE-factor	Degree in which the company complies with the SHE laws and regulations.
4. Preventive maintenance costs / total maintenance costs	Costs of preventive maintenance (labor, material and services) divided by the total maintenance costs.
5. Work orders completed in time	Number of work orders with completion date that is equal to or less than the scheduled completion date divided by the total number of work orders.
6. Technician productivity	Total number of technician hours entered on the equipment-related work orders divided by the total working hours of the technician per annum.
7. Inventory value of spare parts / asset replacement value	Total value of spare parts and repairables on stock divided by the replacement value of the production facility (equipment and equipment-related buildings).
8. Outsourced maintenance cost / total maintenance cost	Cost of outsourced maintenance (services by contractors including material usage) divided by the total maintenance costs.
9. Training costs / total labor costs	Costs of training and education divided by the total labor costs of the maintenance organization
10. Reliability of technical documentation	Number of technical drawings and documents that represent the actual situation of the equipments divided by the total number of technical drawings and documents.

Appendix III – Simulation with Simlox

The Simlox Model

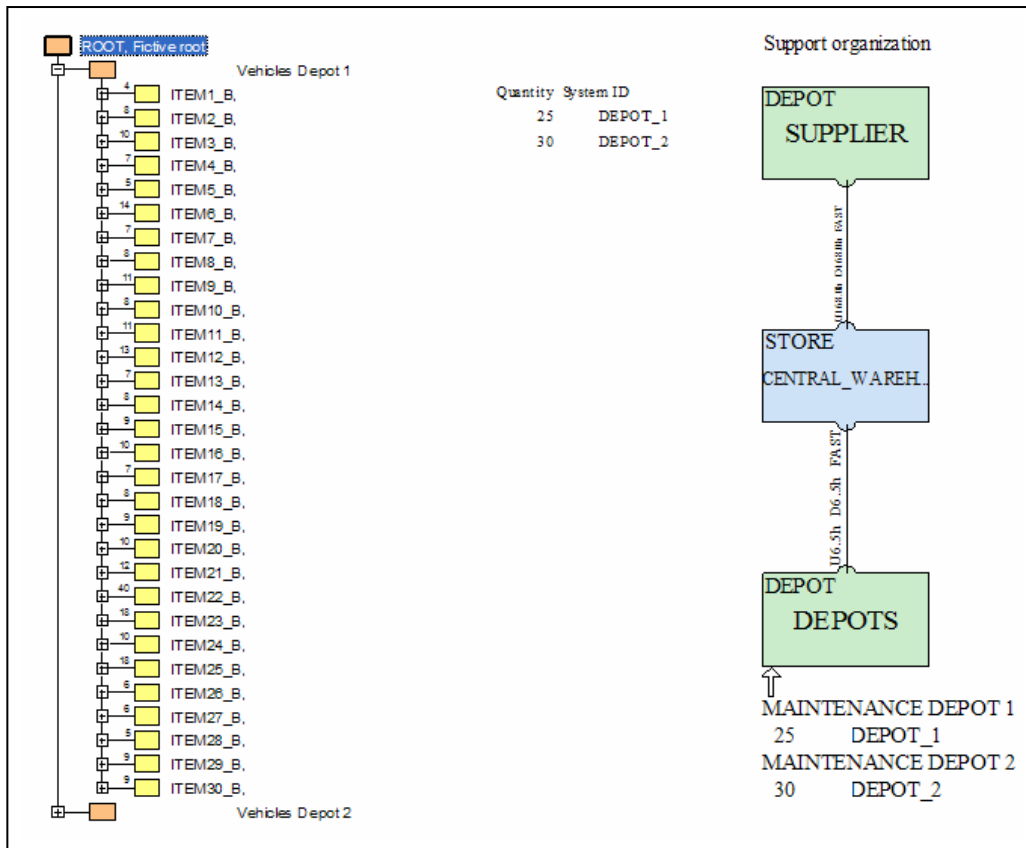
In Simlox all objects are stored in tables and the links between the objects are also defined in tables. Each object has a unique identifier that is used when setting-up the links. The logic is similar to that of a relational database, which makes it easy to communicate with external data sources that are using the same logic, such as databases, spreadsheets, and Systecon's other software tools (Opus10 and Catloc). The table structure is also a very powerful way of organizing and processing large amounts of data, which is necessary when simulating complex structures such as the public transport system.

The interface is straight forward if the user has previous experience from working with databases. However the table structure may be confusing if the user does not have this background. In addition to the basic configuration of 14 tables, there are many extra tables that can be used to model specific scenarios. The total number of tables in the latest Simlox release (version 3.0) adds up to 75. Understanding how all these tables are related and how they can be used to model complex scenarios requires much training, and a continuous use of the software. Despite all the tables there are still situations that can not be modeled in Simlox. In some cases special solutions can help handle these situations, but finding those will require a very deep knowledge of the software.

In Simlox each system must be located at a specific maintenance site. This means that it is not possible to divide the maintenance work on a system between two sites. This option is required for in the public transport case, where heavy maintenance tasks and light maintenance tasks should be carried out at different sites. To handle this problem, the two maintenance sites have to be modeled as one site. Then two types of vehicles with the exact same items must be created to represent the vehicles at each site.

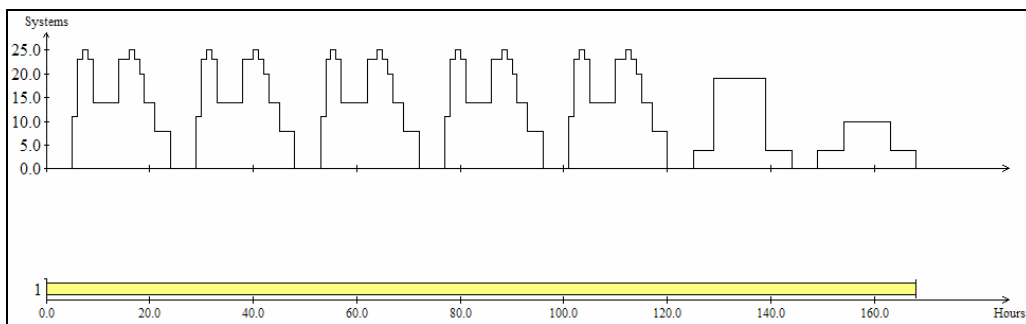
In this model, the maintenance organization includes three levels: the two maintenance sites, a central warehouse, and the supplier. The train fleet consists of 55 vehicles with 30 items each. Optimal stock levels at each site were calculated in Opus10 and exported to Simlox. All items can be repaired/replaced at the maintenance sites, except for two items that must be sent back to the supplier for repair. The total number of repair tracks is limited to 5. Other resources in the maintenance organization such as personnel and tools are unlimited in this simulation.

The Support Organization: A Strategic and Value Adding Force



Simlox model of the vehicle with 30 items, and the related support organization.

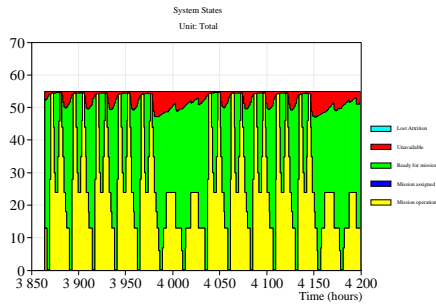
Simlox has a good support for modeling timetables, and in this simulation two different timetables are used – one for the regular season and one for the summer season.



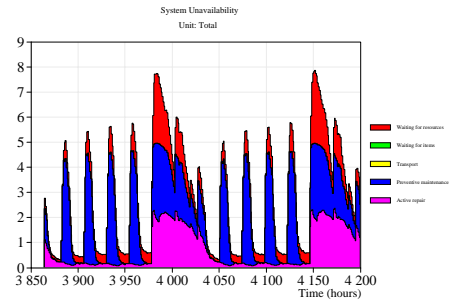
Timetable for one week during regular season.

Simlox Results

The results from the simulation are best described by two graphs – one showing the system states over a week during regular season and one showing the reasons for system unavailability the same week.

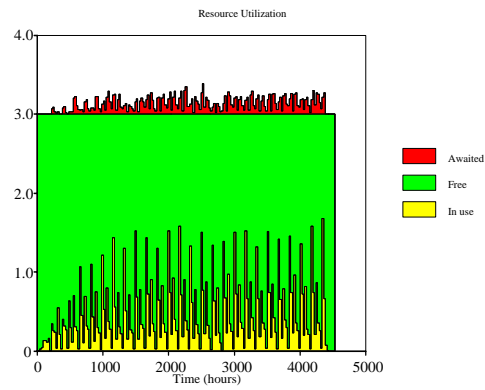
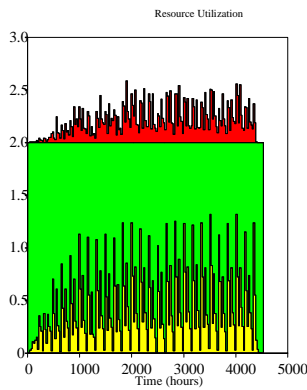


Achieved traffic volume



Cause of system unavailability

The simulation also allows for detailed analyses of the utilization of various resources, for example repair tracks, special tools, maintenance personnel etc.



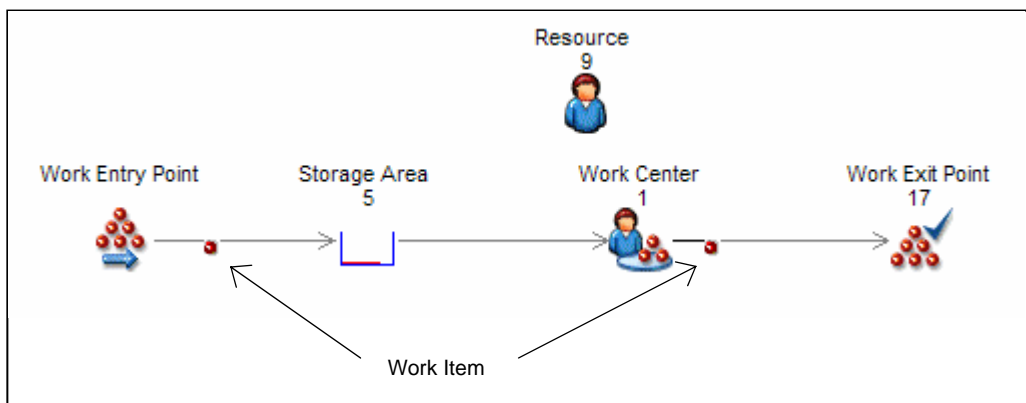
Average utilization of repair tracks at depot 1 and depot 2.

The conclusion from the simulation study was that with the current workload the maintenance organization would achieve the required availability.

Appendix IV – Simulation with Simul8

The Simul8 Model

Simul8 has an intuitive graphical modeling interface. The basic model is built from five standard types of objects representing the most common activities in a workflow. The principle is as follows: Work Items enter the model at a Work Entry Point and are then redirected to a Storage Area. Available Work Centers will pick work items from the storage area and process them before they leave the model at a Work Exit Point. If the work items require special resources (e.g. tools or personnel), then that Resource can be connected to the work centers, and the work item will not be processed until the resource is available.



The basic Simul8 model.

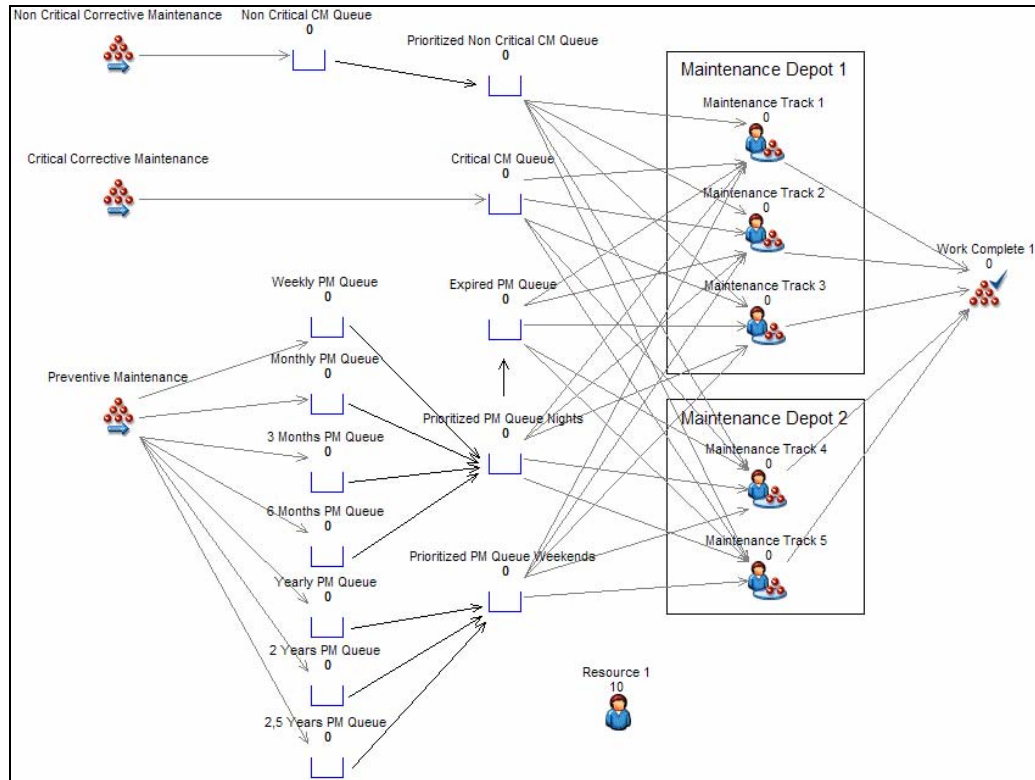
Each object has some standard properties connected to it such as distribution, operation time etc. These properties can easily be adjusted, but more advanced settings must be coded into the model. The programming language used for this is called Visual Logic. It is similar to Visual Basic and includes all the standard programming commands. The coding option gives almost unlimited flexibility in the modeling process, although it will require good programming skills in order to create more complex simulation models.

The basic maintenance organization for the repair track analysis was quickly set up in Simul8, but a great deal of coding was required to incorporate advanced features in the model. The final model includes three work entry points – one for non critical corrective maintenance, one for critical corrective maintenance, and one for preventive maintenance. The vehicles were not modeled as individual systems, but as a group. Hence the MTTF for the corrective maintenance had to vary over time, depending on the number of vehicles on mission. This requires that MTTF has a memoryless distribution, which is true in this case if MTTF is assumed to be exponentially distributed. Features associated with the individual systems could not be included in this model, for example that a system with a certain number of non critical failures should become critical.

Overall it is fairly easy to expand or change the model. Most of the code can be reused if new objects are added to the model, though adding a large number of new types of work items

The Support Organization: A Strategic and Value Adding Force

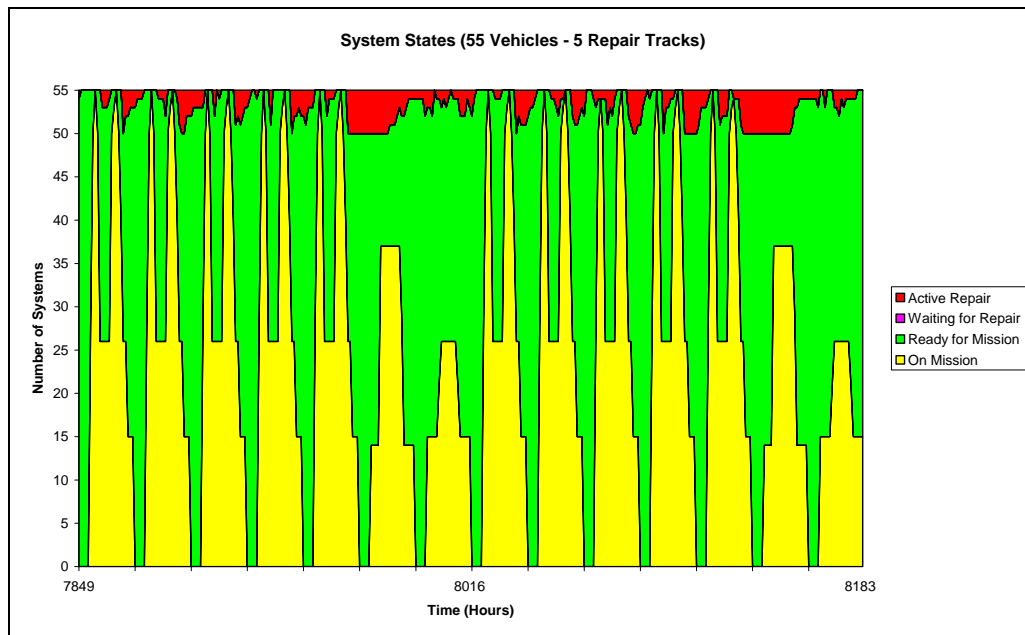
would require much coding. Hence a detailed model of the vehicle would be impractical to work with.



The final Simul8 model.

Simul8 Results

The predefined result views in Simul8 are designed to display the results of a specific object. Results that can easily be displayed are queuing times in the storage areas, utilization of the work centers etc., but there are no predefined graphs that are equivalent to the system state graphs in Simlox. To obtain results like that the current system states must be stored in a matrix during the simulation, and then exported to a spreadsheet program that can create the graphs.



Microsoft Excel graph showing the Simul8 result on the achieved traffic volume.

The Visual Logic Code

```

VL SECTION: Start Run Logic
  SET isTotalNoTrains = 55
  SET isOpWeekday = 0
  SET isOpSaturday = 0
  SET isOpSunday = 0
  LOOP 1 >>> VarY >>> 24
    SET isOpWeekday =
isOpWeekday+[isOperationalProfileWeekday[2,VarY]/isTotalNoTrains
]
    SET isOpWeekday = isOpWeekday*5
    LOOP 1 >>> VarY >>> 24
      SET isOpSaturday =
isOpSaturday+[isOperationalProfileSaturday[2,VarY]/isTotalNoTrains]
    LOOP 1 >>> VarY >>> 24
      SET isOpSunday =
isOpSunday+[isOperationalProfileSunday[2,VarY]/isTotalNoTrains]
    SET isOpPerWeek = [isOpWeekday+isOpSaturday]+isOpSunday
    SET isOpPerYear = 52*isOpPerWeek
    SET isOpFraction = 1/[isOpPerYear]

```

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```
VL SECTION: Time Check Logic
'Define Variables
  SET Critical CM.Batching Out Size = 1
  SET Non Critical CM.Batching Out Size = 1
  SET isTimeOfDay = HOUR[Simulation Time]
  SET isWeekDay = DAY[Simulation Time]
  SET isTrainsOp = 20
  SET isActiveRepair = [[[Maintenance Track 1.Count
Contents+Maintenance Track 2.Count Contents]+Maintenance Track
3.Count Contents]+Maintenance Track 4.Count
Contents]+Maintenance Track 5.Count Contents
'Operational Profile Starts Here
  IF isWeekDay <= 5
    SET isTrainsOp =
isOperationalProfileWeekday[2,isTimeOfDay+1]
    SET isTestTrainsOp = [[isTotalNoTrains-Critical CM
Queue.Count Contents]-Expired PM Queue.Count Contents]-
isActiveRepair
    SET isScheduledTrains = isTrainsOp
    IF isTestTrainsOp < isTrainsOp
      SET isTrainsOp = isTestTrainsOp
  IF isWeekDay = 6
    SET isTrainsOp =
isOperationalProfileSaturday[2,isTimeOfDay+1]
    SET isTestTrainsOp = [[isTotalNoTrains-Critical CM
Queue.Count Contents]-Expired PM Queue.Count Contents]-
isActiveRepair
    SET isScheduledTrains = isTrainsOp
    IF isTestTrainsOp < isTrainsOp
      SET isTrainsOp = isTestTrainsOp
  IF isWeekDay = 7
    SET isTrainsOp =
isOperationalProfileSunday[2,isTimeOfDay+1]
    SET isTestTrainsOp = [[isTotalNoTrains-Critical CM
Queue.Count Contents]-Expired PM Queue.Count Contents]-
isActiveRepair
    SET isScheduledTrains = isTrainsOp
    IF isTestTrainsOp < isTrainsOp
      SET isTrainsOp = isTestTrainsOp
  IF isTrainsOp <= 0
    SET Critical CM.Batching Out Size = 0
    SET Non Critical CM.Batching Out Size = 0
    SET isTrainsOp = 1
'PM Batching Starts Here
  SET Preventive Maintenance.Batching Out Size = 0
  SET isPMInterval = 0
```

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```
SET isCounter = 1
IF Simulation Time = 0
  SET isNextPM = 0
  WHILE isStartTimeVehicle[1,isCounter] <> 99999
    SET PMStartTime = isStartTimeVehicle[1,isCounter]
    SET PMInterval = 168
    SET isStartTimeVehicle[3,isCounter] = [PMStartTime]-
ROUND[0.1*PMInterval]
    SET PMInterval = 730
    SET isStartTimeVehicle[4,isCounter] = [PMStartTime]-
ROUND[0.1*PMInterval]
    SET PMInterval = 2190
    SET isStartTimeVehicle[5,isCounter] = [PMStartTime]-
ROUND[0.1*PMInterval]
    SET PMInterval = 4380
    SET isStartTimeVehicle[6,isCounter] = [PMStartTime]-
ROUND[0.1*PMInterval]
    SET PMInterval = 8760
    SET isStartTimeVehicle[7,isCounter] = [PMStartTime]-
ROUND[0.1*PMInterval]
    SET PMInterval = 17520
    SET isStartTimeVehicle[8,isCounter] = [PMStartTime]-
ROUND[0.1*PMInterval]
    SET PMInterval = 21900
    SET isStartTimeVehicle[9,isCounter] = [PMStartTime]-
ROUND[0.1*PMInterval]
    SET isCounter = isCounter+1
  SET isCounter = 1
  IF Simulation Time = isNextPM
    WHILE isStartTimeVehicle[1,isCounter] <> 99999
      'Weekly PM (1 Week = 168 Hours)
      SET PMInterval = 168
      SET VarX = ROUND[Results Collection
Period/PMInterval]
      SET PMStartTime = isStartTimeVehicle[1,isCounter]
      SET PMBatchSize = isStartTimeVehicle[2,isCounter]
      IF PMStartTime-ROUND[0.1*PMInterval] < 0
        IF Simulation Time = 0
          LOOP 1 >>> VarBatchLoop >>> PMBatchSize
            Add Work To Queue Preventive Maintenance
Event , Weekly PM Queue
            SET PM_Type = 1
            SET PM_Expires =
PMStartTime+ROUND[0.1*PMInterval]
            SET isStartTimeVehicle[3,isCounter] =
[PMStartTime+PMInterval]-ROUND[0.1*PMInterval]
```

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```
      LOOP 0 >>> VarY >>> VarX
        IF Simulation Time =
[PMStartTime+[PMInterval*VarY]]-ROUND[0.1*PMInterval]
          LOOP 1 >>> VarBatchLoop >>> PMBatchSize
            Add Work To Queue    Preventive Maintenance
Event , Weekly PM Queue
          SET PM_Type = 1
          SET PM_Expires =
[PMStartTime+[PMInterval*VarY]]+ROUND[0.1*PMInterval]
            SET isStartTimeVehicle[3,isCounter] =
[PMStartTime+[PMInterval*[VarY+1]]]-ROUND[PMInterval*0.1]
            'Monthly PM (1 Month = 730 Hours)
            SET PMInterval = 730
            SET VarX = ROUND[Results Collection
Period/PMInterval]
            SET PMStartTime = isStartTimeVehicle[1,isCounter]
            SET PMBatchSize = isStartTimeVehicle[2,isCounter]
            IF PMStartTime-ROUND[0.1*PMInterval] < 0
              IF Simulation Time = 0
                LOOP 1 >>> VarBatchLoop >>> PMBatchSize
                  Add Work To Queue    Preventive Maintenance
Event , Monthly PM Queue
                SET PM_Type = 2
                SET PM_Expires =
PMStartTime+ROUND[0.1*PMInterval]
                  SET isStartTimeVehicle[4,isCounter] =
[PMStartTime+PMInterval]-ROUND[0.1*PMInterval]
                LOOP 0 >>> VarY >>> VarX
                  IF Simulation Time =
[PMStartTime+[PMInterval*VarY]]-ROUND[0.1*PMInterval]
                    LOOP 1 >>> VarBatchLoop >>> PMBatchSize
                      Add Work To Queue    Preventive Maintenance
Event , Monthly PM Queue
                    SET PM_Type = 2
                    SET PM_Expires =
[PMStartTime+[PMInterval*VarY]]+ROUND[0.1*PMInterval]
                      SET isStartTimeVehicle[4,isCounter] =
[PMStartTime+[PMInterval*[VarY+1]]]-ROUND[PMInterval*0.1]
                      '3 Months PM (3 Months = 2190 Hours)
                      SET PMInterval = 2190
                      SET VarX = ROUND[Results Collection
Period/PMInterval]
                      SET PMStartTime = isStartTimeVehicle[1,isCounter]
                      SET PMBatchSize = isStartTimeVehicle[2,isCounter]
                      IF PMStartTime-[0.1*PMInterval] < 0
                        IF Simulation Time = 0
```


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```
      LOOP 1 >>> VarBatchLoop >>> PMBatchSize
      Add Work To Queue    Preventive Maintenance
Event , 3 Months PM Queue
      SET PM_Type = 3
      SET PM_Expires = PMStartTime+[0.1*PMInterval]
      SET isStartTimeVehicle[5,isCounter] =
[PMStartTime+PMInterval]-ROUND[0.1*PMInterval]
      LOOP 0 >>> VarY >>> VarX
      IF Simulation Time =
[PMStartTime+[PMInterval*VarY]]-ROUND[0.1*PMInterval]
      LOOP 1 >>> VarBatchLoop >>> PMBatchSize
      Add Work To Queue    Preventive Maintenance
Event , 3 Months PM Queue
      SET PM_Type = 3
      SET PM_Expires =
[PMStartTime+[PMInterval*VarY]]+[0.1*PMInterval]
      SET isStartTimeVehicle[5,isCounter] =
[PMStartTime+[PMInterval*[VarY+1]]]-ROUND[PMInterval*0.1]
      '6 Months PM (6 Months = 4380 Hours)
      SET PMInterval = 4380
      SET VarX = ROUND[Results Collection
Period/PMInterval]
      SET PMStartTime = isStartTimeVehicle[1,isCounter]
      SET PMBatchSize = isStartTimeVehicle[2,isCounter]
      IF PMStartTime-[0.1*PMInterval] < 0
      IF Simulation Time = 0
      LOOP 1 >>> VarBatchLoop >>> PMBatchSize
      Add Work To Queue    Preventive Maintenance
Event , 6 Months PM Queue
      SET PM_Type = 4
      SET PM_Expires = PMStartTime+[0.1*PMInterval]
      SET isStartTimeVehicle[6,isCounter] =
[PMStartTime+PMInterval]-ROUND[0.1*PMInterval]
      LOOP 0 >>> VarY >>> VarX
      IF Simulation Time =
[PMStartTime+[PMInterval*VarY]]-ROUND[0.1*PMInterval]
      LOOP 1 >>> VarBatchLoop >>> PMBatchSize
      Add Work To Queue    Preventive Maintenance
Event , 6 Months PM Queue
      SET PM_Type = 4
      SET PM_Expires =
[PMStartTime+[PMInterval*VarY]]+[0.1*PMInterval]
      SET isStartTimeVehicle[6,isCounter] =
[PMStartTime+[PMInterval*[VarY+1]]]-ROUND[PMInterval*0.1]
      'Yearly PM (1 Year = 8760 Hours)
      SET PMInterval = 8760
```

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```
        SET VarX = ROUND[Results Collection
Period/PMInterval]
        SET PMStartTime = isStartTimeVehicle[1,isCounter]
        SET PMBatchSize = isStartTimeVehicle[2,isCounter]
        IF PMStartTime-[0.1*PMInterval] < 0
            IF Simulation Time = 0
                LOOP 1 >>> VarBatchLoop >>> PMBatchSize
                    Add Work To Queue    Preventive Maintenance
Event , Yearly PM Queue
        SET PM_Type = 5
        SET PM_Expires = PMStartTime+[0.1*PMInterval]
        SET isStartTimeVehicle[7,isCounter] =
[PMStartTime+PMInterval]-ROUND[0.1*PMInterval]
        LOOP 0 >>> VarY >>> VarX
            IF Simulation Time =
[PMStartTime+[PMInterval*VarY]]-ROUND[0.1*PMInterval]
                LOOP 1 >>> VarBatchLoop >>> PMBatchSize
                    Add Work To Queue    Preventive Maintenance
Event , Yearly PM Queue
        SET PM_Type = 5
        SET PM_Expires =
[PMStartTime+[PMInterval*VarY]]+ROUND[0.1*PMInterval]
        SET isStartTimeVehicle[7,isCounter] =
[PMStartTime+[PMInterval*[VarY+1]]]-ROUND[PMInterval*0.1]
        '2 Years PM (2 Years = 17520 Hours)
        SET PMInterval = 17520
        SET VarX = ROUND[Results Collection
Period/PMInterval]
        SET PMStartTime = isStartTimeVehicle[1,isCounter]
        SET PMBatchSize = isStartTimeVehicle[2,isCounter]
        IF PMStartTime-[0.1*PMInterval] < 0
            IF Simulation Time = 0
                LOOP 1 >>> VarBatchLoop >>> PMBatchSize
                    Add Work To Queue    Preventive Maintenance
Event , 2 Years PM Queue
        SET PM_Type = 6
        SET PM_Expires = PMStartTime+[0.1*PMInterval]
        SET isStartTimeVehicle[8,isCounter] =
[PMStartTime+PMInterval]-ROUND[0.1*PMInterval]
        LOOP 0 >>> VarY >>> VarX
            IF Simulation Time =
[PMStartTime+[PMInterval*VarY]]-ROUND[0.1*PMInterval]
                LOOP 1 >>> VarBatchLoop >>> PMBatchSize
                    Add Work To Queue    Preventive Maintenance
Event , 2 Years PM Queue
        SET PM_Type = 6
```

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```
        SET PM_Expires =
[PMStartTime+[PMInterval*VarY]]+ROUND[0.1*PMInterval]
        SET isStartTimeVehicle[8,isCounter] =
[PMStartTime+[PMInterval*[VarY+1]]]-ROUND[PMInterval*0.1]
'2,5 Years PM (2,5 Years = 21900 Hours)
        SET PMInterval = 21900
        SET VarX = ROUND[Results Collection
Period/PMInterval]
        SET PMStartTime = isStartTimeVehicle[1,isCounter]
        SET PMBatchSize = isStartTimeVehicle[2,isCounter]
        IF PMStartTime-[0.1*PMInterval] < 0
        IF Simulation Time = 0
        LOOP 1 >>> VarBatchLoop >>> PMBatchSize
        Add Work To Queue Preventive Maintenance
Event , 2,5 Years PM Queue
        SET PM_Type = 7
        SET PM_Expires = PMStartTime+[0.1*PMInterval]
        SET isStartTimeVehicle[9,isCounter] =
[PMStartTime+PMInterval]-ROUND[0.1*PMInterval]
        LOOP 0 >>> VarY >>> VarX
        IF Simulation Time =
[PMStartTime+[PMInterval*VarY]]-ROUND[0.1*PMInterval]
        LOOP 1 >>> VarBatchLoop >>> PMBatchSize
        Add Work To Queue Preventive Maintenance
Event , 2,5 Years PM Queue
        SET PM_Type = 7
        SET PM_Expires =
[PMStartTime+[PMInterval*VarY]]+ROUND[0.1*PMInterval]
        SET isStartTimeVehicle[9,isCounter] =
[PMStartTime+[PMInterval*[VarY+1]]]-ROUND[PMInterval*0.1]
        SET isCounter = isCounter+1
        SET isCounter = 1
        SET isNextPM = isStartTimeVehicle[3,isCounter]
        WHILE isStartTimeVehicle[1,isCounter] <> 99999
        IF isStartTimeVehicle[3,isCounter] < isNextPM
        SET isNextPM = isStartTimeVehicle[3,isCounter]
        IF isStartTimeVehicle[4,isCounter] < isNextPM
        SET isNextPM = isStartTimeVehicle[4,isCounter]
        IF isStartTimeVehicle[5,isCounter] < isNextPM
        SET isNextPM = isStartTimeVehicle[5,isCounter]
        IF isStartTimeVehicle[6,isCounter] < isNextPM
        SET isNextPM = isStartTimeVehicle[6,isCounter]
        IF isStartTimeVehicle[7,isCounter] < isNextPM
        SET isNextPM = isStartTimeVehicle[7,isCounter]
        IF isStartTimeVehicle[8,isCounter] < isNextPM
        SET isNextPM = isStartTimeVehicle[8,isCounter]
```

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```
IF isStartTimeVehicle[9,isCounter] < isNextPM
  SET isNextPM = isStartTimeVehicle[9,isCounter]
  SET isCounter = isCounter+1
'Routing of Expired PM
  IF Prioritized PM Queue Nights.Count Contents > 0
    SET Qpos = 0
    WHILE Qpos < Prioritized PM Queue Nights.Count Contents
      SET Qpos = Qpos+1
      Select Current Work Item    Prioritized PM Queue Nights
, Qpos
      IF PM_Expires <= Simulation Time
        Move Work Item To    Expired PM Queue , -1
  IF Yearly PM Queue.Count Contents > 0
    SET Qpos = 0
    WHILE Qpos < Yearly PM Queue.Count Contents
      SET Qpos = Qpos+1
      Select Current Work Item    Yearly PM Queue , Qpos
      IF PM_Expires <= Simulation Time
        Move Work Item To    Expired PM Queue , -1
'Time Based Rerouting of PM to Prioritized Queues
'Weekly PM
  IF Weekly PM Queue.Count Contents > 0
    SET Qpos = 0
    WHILE Qpos < Weekly PM Queue.Count Contents
      Select Current Work Item    Weekly PM Queue , 1
      IF PM_Type = 1
        Move Work Item To    Prioritized PM Queue Nights ,
-1
      IF isWeekDay <> 6
        IF isWeekDay <> 7
          IF isTimeOfDay > 4
            IF isTimeOfDay < 9
              IF Prioritized PM Queue Nights.Count Contents >
0
                SET Qpos = 0
                WHILE Qpos < Prioritized PM Queue Nights.Count
Contents
                  SET Qpos = Qpos+1
                  Select Current Work Item    Prioritized PM
Queue Nights , Qpos
                    IF PM_Type = 1
                      Move Work Item To    Weekly PM Queue , -1
                      SET Qpos = Qpos-1
                    IF isTimeOfDay > 12
                      IF isTimeOfDay < 18
```

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```

    IF Prioritized PM Queue Nights.Count Contents >
0
        SET Qpos = 0
        WHILE Qpos < Prioritized PM Queue
Nights.Count Contents
            SET Qpos = Qpos+1
            Select Current Work Item    Prioritized PM
Queue Nights , Qpos
                IF PM_Type = 1
                    Move Work Item To    Weekly PM Queue , -1
                    SET Qpos = Qpos-1
'Monthly PM
    IF Monthly PM Queue.Count Contents > 0
        SET Qpos = 0
        WHILE Qpos < Monthly PM Queue.Count Contents
            Select Current Work Item    Monthly PM Queue , 1
            IF PM_Type = 2
                Move Work Item To    Prioritized PM Queue Nights ,
-1
    IF isWeekDay <> 6
        IF isWeekDay <> 7
            IF isTimeOfDay < 18
                IF Prioritized PM Queue Nights.Count Contents > 0
                    SET Qpos = 0
                    WHILE Qpos < Prioritized PM Queue Nights.Count
Contents
                        SET Qpos = Qpos+1
                        Select Current Work Item    Prioritized PM Queue
Nights , Qpos
                            IF PM_Type = 2
                                Move Work Item To    Monthly PM Queue , -1
                                SET Qpos = Qpos-1
'3 Months PM
    IF 3 Months PM Queue.Count Contents > 0
        SET Qpos = 0
        WHILE Qpos < 3 Months PM Queue.Count Contents
            Select Current Work Item    3 Months PM Queue , 1
            IF PM_Type = 3
                Move Work Item To    Prioritized PM Queue Nights ,
-1
    IF isWeekDay <> 6
        IF isWeekDay <> 7
            IF isTimeOfDay > 1
                IF isTimeOfDay < 9
                    IF Prioritized PM Queue Nights.Count Contents >
0
```

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```

        SET Qpos = 0
        WHILE Qpos < Prioritized PM Queue Nights.Count
Contents
            SET Qpos = Qpos+1
            Select Current Work Item    Prioritized PM
Queue Nights , Qpos
                IF PM_Type = 3
                    Move Work Item To    3 Months PM Queue , -1
                    SET Qpos = Qpos-1
        IF isTimeOfDay > 9
        IF isTimeOfDay < 18
            IF Prioritized PM Queue Nights.Count Contents >
0
                SET Qpos = 0
                WHILE Qpos < Prioritized PM Queue
Nights.Count Contents
                    SET Qpos = Qpos+1
                    Select Current Work Item    Prioritized PM
Queue Nights , Qpos
                        IF PM_Type = 3
                            Move Work Item To    3 Months PM Queue ,
-1
                                SET Qpos = Qpos-1
        '6 Months PM
        IF 6 Months PM Queue.Count Contents > 0
            SET Qpos = 0
            WHILE Qpos < 6 Months PM Queue.Count Contents
                Select Current Work Item    6 Months PM Queue , 1
                IF PM_Type = 4
                    Move Work Item To    Prioritized PM Queue Nights ,
-1
        IF isWeekDay <> 6
            IF isWeekDay <> 7
                IF isTimeOfDay > 0
                IF isTimeOfDay < 18
                    IF Prioritized PM Queue Nights.Count Contents >
0
                        SET Qpos = 0
                        WHILE Qpos < Prioritized PM Queue Nights.Count
Contents
                            SET Qpos = Qpos+1
                            Select Current Work Item    Prioritized PM
Queue Nights , Qpos
                                IF PM_Type = 4
                                    Move Work Item To    6 Months PM Queue , -1
                                    SET Qpos = Qpos-1

```

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```
'Yearly PM
  IF isWeekDay = 5
    IF isTimeOfDay > 18
      IF Yearly PM Queue.Count Contents > 0
        SET Qpos = 0
        WHILE Qpos < Yearly PM Queue.Count Contents
          Select Current Work Item Yearly PM Queue , 1
          Move Work Item To Prioritized PM Queue Weekends
, -1
  IF isWeekDay = 6
    IF isTimeOfDay < 21
      IF Yearly PM Queue.Count Contents > 0
        SET Qpos = 0
        WHILE Qpos < Yearly PM Queue.Count Contents
          Select Current Work Item Yearly PM Queue , 1
          Move Work Item To Prioritized PM Queue Weekends
, -1
  IF isWeekDay = 6
    IF isTimeOfDay >= 21
      IF Prioritized PM Queue Weekends.Count Contents > 0
        SET Qpos = 0
        WHILE Qpos < Prioritized PM Queue Weekends.Count
Contents
          SET Qpos = Qpos+1
          Select Current Work Item Prioritized PM Queue
Weekends , Qpos
          IF PM_Type = 5
            Move Work Item To Yearly PM Queue , -1
            SET Qpos = Qpos-1
'2 Years PM
  IF isWeekDay = 5
    IF isTimeOfDay > 18
      IF 2 Years PM Queue.Count Contents > 0
        SET Qpos = 0
        WHILE Qpos < 2 Years PM Queue.Count Contents
          Select Current Work Item 2 Years PM Queue , 1
          Move Work Item To Prioritized PM Queue Weekends
, -1
  IF isWeekDay = 6
    IF isTimeOfDay <= 23
      IF 2 Years PM Queue.Count Contents > 0
        SET Qpos = 0
        WHILE Qpos < 2 Years PM Queue.Count Contents
          Select Current Work Item 2 Years PM Queue , 1
          Move Work Item To Prioritized PM Queue Weekends
, -1
```

The Support Organization: A Strategic and Value Adding Force

```
IF isWeekDay = 7
  IF isTimeOfDay >= 12
    IF Prioritized PM Queue Weekends.Count Contents > 0
      SET Qpos = 0
      WHILE Qpos < Prioritized PM Queue Weekends.Count
Contents
        SET Qpos = Qpos+1
        Select Current Work Item    Prioritized PM Queue
Weekends , Qpos
          IF PM_Type = 6
            Move Work Item To    2 Years PM Queue , -1
            SET Qpos = Qpos-1
'2,5 Years PM
  IF isWeekDay = 5
    IF isTimeOfDay > 18
      IF 2,5 Years PM Queue.Count Contents > 0
        SET Qpos = 0
        WHILE Qpos < 2,5 Years PM Queue.Count Contents
          Select Current Work Item    2,5 Years PM Queue ,
1
            Move Work Item To    Prioritized PM Queue Weekends
, -1
  IF isWeekDay = 6
    IF isTimeOfDay <= 23
      IF 2,5 Years PM Queue.Count Contents > 0
        SET Qpos = 0
        WHILE Qpos < 2,5 Years PM Queue.Count Contents
          Select Current Work Item    2,5 Years PM Queue ,
1
            Move Work Item To    Prioritized PM Queue Weekends
, -1
  IF isWeekDay = 7
    IF isTimeOfDay >= 9
      IF Prioritized PM Queue Weekends.Count Contents > 0
        SET Qpos = 0
        WHILE Qpos < Prioritized PM Queue Weekends.Count
Contents
          SET Qpos = Qpos+1
          Select Current Work Item    Prioritized PM Queue
Weekends , Qpos
            IF PM_Type = 7
              Move Work Item To    2,5 Years PM Queue , -1
              SET Qpos = Qpos-1
'Time Based Rerouting of Non Critical CM to Prioritized Queue
'Non Critical CM
  IF Non Critical CM Queue.Count Contents > 0
```


The Support Organization: A Strategic and Value Adding Force

```
SET Qpos = 0
WHILE Qpos < Non Critical CM Queue.Count Contents
  SET Qpos = Qpos+1
  Select Current Work Item Non Critical CM Queue ,
Qpos
  Move Work Item To Prioritized Non Critical CM
Queue , -1
  IF isWeekDay <> 6
    IF isWeekDay <> 7
      IF isTimeOfDay > 2
        IF isTimeOfDay < 9
          IF Prioritized Non Critical CM Queue.Count
Contents > 0
            SET Qpos = 0
            WHILE Qpos < Prioritized Non Critical CM
Queue.Count Contents
              SET Qpos = Qpos+1
              Select Current Work Item Prioritized Non
Critical CM Queue , Qpos
              Move Work Item To Non Critical CM Queue ,
-1
              IF isTimeOfDay > 10
                IF isTimeOfDay < 18
                  IF Prioritized Non Critical CM Queue.Count
Contents > 0
                    SET Qpos = 0
                    WHILE Qpos < Prioritized Non Critical CM
Queue.Count Contents
                      SET Qpos = Qpos+1
                      Select Current Work Item Prioritized Non
Critical CM Queue , Qpos
                      Move Work Item To Non Critical CM Queue
, -1
                    'Creating Result Output
                    IF Simulation Time > 17520
                      SET isResults[1,Simulation Time-17520] =
isScheduledTrains
                      SET isResults[2,Simulation Time-17520] = isTrainsOp
                      SET isResults[3,Simulation Time-17520] = isTestTrainsOp
                      SET isResults[4,Simulation Time-17520] = Critical CM
Queue.Count Contents+Expired PM Queue.Count Contents
                      SET isResults[5,Simulation Time-17520] = isActiveRepair
                      SET isResults[6,Simulation Time-17520] = [Prioritized
Non Critical CM Queue.Count Contents+Prioritized PM Queue
Nights.Count Contents]+Prioritized PM Queue Weekends.Count
Contents
```

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ReSchedule Arrival Critical CM
ReSchedule Arrival Non Critical CM

VL SECTION: Maintenance Track 1-5 Route-In Before Logic
'Allow only Stopping CM and Expired PM if Operational Profile
is not fullfilled

```
IF isWeekDay <= 5
  SET isTrainsOp =
isOperationalProfileWeekday[2,isTimeOfDay+1]
  SET isTestTrainsOp = [[isTotalNoTrains-Critical CM
Queue.Count Contents]-Expired PM Queue.Count Contents]-
isActiveRepair
  IF isTestTrainsOp <= isTrainsOp
    SET isTrainsOp = isTestTrainsOp
    IF Critical CM Queue.Count Contents <= 0
      IF Expired PM Queue.Count Contents <= 0
        Block Current Routing
  IF isTrainsOp <= 0
    SET Critical CM.Batching Out Size = 0
    SET isTrainsOp = 1
```

VL SECTION: Maintenance Track 1-5 Route-In After Logic
Select Current Work Item Maintenance Track 1 , 1
SET isWorkItemName = Current Work Item
IF isWorkItemName = "Non Critical CM Event"
 SET Maintenance Track 1.Operation Time = 4
IF isWorkItemName = "Critical CM Event"
 SET Maintenance Track 1.Operation Time = 4
IF isWorkItemName = "Preventive Maintenance Event"
 IF PM_Type = 1
 SET Maintenance Track 1.Operation Time = 1.5
 IF PM_Type = 2
 SET Maintenance Track 1.Operation Time = 7
 IF PM_Type = 3
 SET Maintenance Track 1.Operation Time = 5
 IF PM_Type = 4
 SET Maintenance Track 1.Operation Time = 6
 IF PM_Type = 5
 SET Maintenance Track 1.Operation Time = 33
 IF PM_Type = 6
 SET Maintenance Track 1.Operation Time = 18
 IF PM_Type = 7
 SET Maintenance Track 1.Operation Time = 12