Propositions
accompanying the dissertation

Railway Design and Maintenance from a Life-Cycle Cost Perspective: A
Decision-Support Approach
Arjen Zoeteman, November 22, 2004

1. Serious progress in the quality of rail infrastructure management in the
Netherlands is only possible, if the ‘quality assurance’ at central level, being
part of the maintenance planning process, is significantly enhanced.

2. Life-cycle costing is also a highly suitable method for prioritising projects or
activities in the case of shrinking budgets. Unfortunately, budgets are usually
cut down in that situation, using the ‘cheeseslicer method’

3. A performance regime will not turn out to be a serious stimulus for improved
infrastructure management, as long as it is not linked to the financial input of
the infrastructure manager.

4. The fact that low-cost carriers can offer a safe product in the airline industry
demonstrates how far the progress in maintenance management is in that
sector.

5. ‘Safety margins are not chosen on the basis of analysis; they rather serve as a
substitute for analysis.’¹ Taxpayers are disadvantaged because “safety” is also
used in the rail infrastructure sector as an excuse not to (need to) further
review the quality of existing ways of acting.

6. A Parliament that would take its role in society seriously, should already have
investigated the current course of business concerning the Zuiderzeeline
during the parliamentary investigation ‘Mega Projects’ (in 2004).

7. It is not at all a problem for the Dutch ‘Knowledge Society’ that PhD students
from abroad more and more populate the exact sciences, as long as there are
enough Dutch researchers to give them a warm welcome.

¹ This means that an equal reduction is applied to all project budgets.
Conference on Technology, Policy and Management, TU Delft.
8. The ultimate mode of (societal) integration is emigration, alone and to a far-away country; all other 'integration exercises' are sub-optimal.

9. 'Physics is the most difficult path towards a low salary.'\(^1\) Based on this revealed preference, it can be concluded that physicists do their job with the most inherent job satisfaction.

10. Sport Utility Vehicles (SUVs) are the least "sporty" cars (in relation to other road users), with the most useless car bodies.

11. Aggressive computer games are good for young people. This is how they learn that, sooner or later (i.e. at a certain 'level'), it will be game-over if you can only fight well.

12. The argument of 'horizon pollution' (the visual impact on the landscape) to prevent windmills from being constructed will not be valid anymore, once windmills and the well-known McDonald's' masts are integrated.\(^3\)

*These propositions are considered defendable and thus have been approved by the supervisors prof.dr.ir. R.E.C.M. van der Heijden and prof.dr.ir. C. Esveld.*

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\(^1\) Proposition 12, accompanying the dissertation 'Atomic-scale electronics in semiconductors', G.-J. Smit, DUT.

\(^3\) This proposition is based on a suggestion of Rolf Dollevoet.
1. Serieuze voortgang in de kwaliteit van het ‘infrabeheer’ proces op het Nederlandse spoor is alleen mogelijk indien de kwaliteitsborging op centraal niveau, als onderdeel van het onderhoudsplanningsproces, aanzienlijk wordt versterkt.

2. Ook bij krimpende budgetten blijft life-cycle costing een uitermate geschikte methode om optimale (project-)prioriteiten te stellen. Helaas worden budgetten in deze situatie doorgaans met de kaasschaafmethode gekort.*

3. Een prestatiecontract zal geen serieuze stimulans tot verbetering zijn voor de infrabeheerder, zolang deze niet gekoppeld is met de financiële input van deze infrabeheerder.

4. ‘Safety margins are not chosen on the basis of analysis; they rather serve as a substitute for analysis.’† De belastingbetaalder wordt benadeeld doordat “veiligheid” binnen de railinfrasector ook als excuus gehanteerd wordt om bestaande handelwijzen niet verder ter discussie te (hoeven) stellen.

5. Het feit dat prijsscheppers in de luchtvaart een veilig product kunnen leveren geeft aan hoe ver de voortgang in onderhoudsmanagement is in die sector.

6. Een Parlement dat haar rol echt serieus zou nemen, had ook reeds de gang van zaken rond de Zuiderzeelijn onderzocht tijdens het parlementaire onderzoek ‘Grote Projecten’.

7. Het is geen enkel probleem voor “Nederland Kennisland” dat de betastudies steeds meer bevolkt worden door buitenlandse promovendi, zolang er genoeg Nederlandse onderzoekers overblijven om ze een warm welkom te heten.

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* D.w.z. van alle projecten wordt een gelijkwaardig deel budget geschrapt.
8. De uitele vorm van "integreren" is emigreren, in je eentje en naar een verland; alle andere vormen van integreren zijn suboptimaal.

9. 'Natuurkunde is de moeilijkste weg naar een laag inkomen.' Op basis van deze 'onthulde voorkeur' kan geconcludeerd worden dat het de natuurkundigen zijn die hun werk doen met de grootst mogelijke intrinsieke arbeidsvreugde.

10. Sport Utility Vehicles (SUVs) zijn de minst sportieve auto's met de meest nutteloze casco's.

11. Agressieve computerspelen zijn goed voor de jeugd. Zo leert men dat het vroeg of laat game-over is (c.q. op enig 'level'), als je alleen maar goed kan vechten.

12. Indien windmolens en de overbekende 'Mac Donald's palen' geïntegreerd worden, vervalt in ieder geval het argument van horizonvervuiling tegen windmolens.

Deze stellingen worden verdedigbaar geacht en zijn als zodanig goedgekeurd door de promotoren prof.dr.ir. R.E.C.M. van der Heijden and prof.dr.ir. C. Esveld.

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* Stelling 12, behorende bij het proefschrift Atomic-scale electronics in semiconductors, G.-J. Smit (2004), TUD.
* Gebaseerd op een suggestie van Dolf Rollevoet.
Railway Design and Maintenance from a Life-Cycle Cost Perspective

A Decision-Support Approach
Railway Design and Maintenance from a Life-Cycle Cost Perspective

A Decision-Support Approach

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft
op gezag van de Rector Magnificus prof.dr.ir. J.T. Fokkema
voorzitter van het College van Promoties,
in het openbaar te verdedigen op maandag 22 november 2004 om 15.30 uur

door Arjen ZOETEMAN

bestuurskundig ingenieur
geboren te Gouda
Dit proefschrift is goedgekeurd door de promotoren:
Prof.dr.ir. R.E.C.M. van der Heijden
Prof.dr.ir. C. Esveld

Samenstelling promotiecommissie:

Rector Magnificus, voorzitter
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TRAIL Thesis Series nr. T2004/7, The Netherlands TRAIL Research School

Published and distributed by:

TRAIL Research School
P.O. Box 5017
2600 GA Delft, The Netherlands
T +31 15 278 60 46
F +31 15 278 43 33
E info@rsTRAIL.nl
I www.rsTRAIL.nl

ISBN 90-5584-058-0

Keywords: railway infrastructure, maintenance, life-cycle costing, decision support

Cover photo: Roel de Vringer, with the permission of Uitgeverij Kerkebosch and the ‘Weg &Werken Vereniging (discontinued in 2000)’
Cover design: Joke Herstel, Wenk

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Printed in The Netherlands
Preface

'For which of you, intending to build a tower, sitteth not down first, and counteth the cost, whether he have sufficient to finish it?'

Luke 14:28

Books on costs and maintenance, and certainly those concerning the combination of the two, are generally not bought on impulse. The reason is evident. Whereas the design of new systems and products often has an image of novelty and improvement, the process of analysing and 'engineering' future maintenance needs, costs and system breakdowns lacks this image entirely. In many industries and infrastructure systems, maintenance has traditionally been approached as something that was simply sometimes required, but not something that required proactive managing.

Fortunately, this picture has changed over the last decade or two, as issues such as safety, reliability, availability and affordability (life-cycle costs) have become more and more important. This book proves that this also, gradually, happens to be the case in the European railways, and for good reasons. Railway maintenance and renewal (M&R) matters today, even if only looking at the direct expenditures. The International Union of Railways reported that M&R expenditures on the Western European network amounted to approximately €12 billion in 2000, surpassing the €8 billion spent on new rail infrastructure that year [UIC, 2002]. These expenditures, set against the relatively low transport volumes, are an important cause of the unfavourable cost/performance ratio of the 'rail' mode.

Maintenance costs, including the impacts of system closures and breakdowns, should thus form a decisive key to improving the performance of the railways. Analysis of these costs could reveal whether too much money is spent on ineffective work, or too little money is spent on effective work, in terms of system reliability and durability. Based on detailed cost and condition data, it should be possible to locate root causes of performance problems and to determine fairly accurately which interventions will be beneficial.

However it appears that progress in the European railways regarding that search for value for money is still slow. Required data on maintenance and maintenance-dependent costs, which explain what factors cause what costs, related to which objects (assets), are often unavailable. This leads to a 'chicken and egg problem': it is difficult to develop well-founded
cost analyses, but without actually starting such analysis, it is impossible to evaluate and improve the assumptions underlying the current way of working.

The 'philosophy' underlying this study is that rail infrastructure managers should be encouraged to work step-by-step towards such a proactive approach to managing maintenance (and thereby performance) and to create a better knowledge of costs. The study is particularly set up from a 'policy analysis' viewpoint and has an explorative nature; its aim is to analyse whether and how decision-makers in the rail sector can be assisted in identifying and adopting design and maintenance strategies, which take ‘life-cycle’ impacts into account.

The study started seven years ago, when I became deeply involved in the railway world – known for not being the most uncomplicated of worlds (but certainly fascinating). There is a very small chance that it was my father who kept saying that ‘but is this not what you are educated for?’, when I arrived home with yet another delay (using other terminology). However, a more likely explanation is that I jumped in, simply because the Master's project that I was offered was just great. It started with an e-mail from the Railway Engineering group to the Faculty of Technology, Policy and Management (TPM), enquiring whether they could find a student for a research project for the Regional Government of Madrid. I jumped in, because this Spanish adventure appeared quite attractive. And so it was. During my stay in Madrid, Prof. Manuel Melis and Ildefonso de Matias gave me the opportunity to take part in the process concerning the 'booming' Madrid Metro network; it was unforgettable. Because the approach taken appeared to be useful, I decided in cooperation with Prof. Van der Heijden and Prof. Esveld to continue with a PhD project. I must admit that I still wondered at the time how one should do or manage such a ‘thing’ (if only I’d...). Keen sponsors of the project were, however, instantly found in Strukton Railinfra, Railinfrabeheer (now part of ProRail) and the European Rail Research Institute. Strukton had already provided a Dutch home base during the Master’s project.

Over the past few years, I have been able to discuss my research with many people, whom I will not try to list here (see Appendix A for a list of international interviewees and the VIPs who participated in the case studies). There are, however, a few exceptions. First of all, there are my thesis supervisors, Prof. Rob van der Heijden and Prof. Coenraad Esveld. I owe Rob a debt of gratitude for allowing me the freedom to find my own path, while never forgetting those issues that come with scientific research. This was surely the best way for me (though we cannot verify this through scientific experiment). I am grateful to Coen for introducing me so well to the sector and for his critical reflections regarding technical issues and 'the way forward' for the rail sector.

Starting with something new is always difficult. I owe therefore many thanks to Egbert Braaksma, Marco Reef, Frits Schippers, Diederik Schonebaum, Aike Schools, Erland Tegelberg at Strukton, and to Linda van der Eijck, Ollie Olsthoorn and Jan Swier at Railinfrabeheer/ProRail, who believed in my research from the beginning. I have always considered the open attitude of Strukton Railinfra and ProRail, in allowing me to 'meddle' in a few important projects, unique. I admire the open mind with which my findings and suggestions were recently received by the ProRail management as well as the enthusiasm with which the people from Strukton and ProRail have supported my research. This research was only possible, because they were willing to share so much knowledge and experience.
Further, my gratitude goes to the ‘LCM+ core team’ colleagues Kees Loef and Rob van Zelm – I would like to remind you that we still have to set up our special consulting firm, or at least drink a beer together… Also, I would like to thank Steffen Knape for his support in the HSL South project, Jan Zwarthoed for one of the LCM+ pilots, Prof. Yoshihiko Sato for arranging my visit to Japan, and Dr. Peter Veit, Sjoerd Gallmann and Peter de Weijs for co-authoring papers. Special thanks go to Stasha Jovanovic for many animated discussions.

I was fortunate to meet many rail, transport and infrastructure professionals through the meetings of the TRAIL Research School, the KIVI-NIRIA Department of Traffic and Transport Engineering (V&V) and the Delft TopTech School. I especially thank my colleagues at the V&V Board for our inspiring discussions and Prof. Ingo Hansen for inviting me to take the enjoyable position of project coach in the Rail Systems Engineering course.

I thank all my colleagues at the Transport Policy and Logistics’ Organisation group for a very pleasant working atmosphere. Of the many nice TPM roommates, I would especially like to thank Ellen Jagtman and Ilona Bos, with whom I spent the most time – this was certainly not a punishment! I already miss TLO’s vibrant ‘sectie-uitjes’ and the room facing the secretariat, which always led to wonderful mini-conferences with Trudie, Betty and Ellen (special thanks to Trudie for all the practical support during many years!). On the other hand, I have now found a new base among the enthusiastic (and sporty!) group of professionals, well-known as the Road and Railway Engineering Section and Laboratory. I would particularly like to mention my roommate, Patrick Muraya, with whom I am studying the nuances of Dutch language (e.g. the difference between koffie verkeerd and verkeerde koffie), and Ivan Shevtsov for the ‘PDF-support’ (thanks!).

Finally, I would like to thank the invaluable home-front: ‘pap & mam’, for the endless support; Gerda, Ruud, Marianne and Maaike; the Fam. Van Gaalen, Jothijs and Annerieke, my dear friends Gert-Jan and Hennie, Wouter, Manoël and Cris, Cornoé, Ellen and Jan-Pascal, Marcel and Lidewine, as well as many other friends from my ‘Goudse leven’. I would like to apologise for always being too rushed over the last few years, and this apology is particularly addressed to Johanna. Somehow you never got tired of my endless stream of complaints during the last two years regarding this piece of work, which is the truly important ‘finding’ from my research work. ¡Te quiero mucho, mi vida!

Arjen Zoeteman
Gouda, 30 September 2004
With reference to the operation of railroads after they have been completed, the following propositions may be regarded as among the most prominent of those that have been established by experience:

1. The road and outfit should always be of first class; and kept in perfect condition.
2. The control of the operating department should always be in the hands of men of sound judgment, large experience and inflexible honesty.
3. Persons holding high and responsible positions in the management of a railroad, should always be invested with power commensurate with their responsibility.
4. Perfect discipline and subordination are as essential to the good management of a railroad as they are to the success of an army.
5. The employees upon a railroad who have business intercourse with its patrons, or the public, should be men of integrity, gentlemanly manners, firm purpose and unexcitable temper.
6. The true and only sources of revenue and profit to railroad companies, is the local business naturally pertaining to the country and towns through which the road passes or at which it terminates. This business should always be encouraged by doing it upon the most reasonable terms, and to the satisfaction of those who create it.
7. The effort to secure a larger amount of through business than would normally follow the route of the road, from points beyond its extremities, where other lines are competing for the same business, is generally attended with disappointments and damage to the true interests of the company.
8. The expenses of operating well managed roads, are generally from fifty to sixty per cent of their gross earnings.
9. The wear and tear of track and machinery are very nearly in the ratio of the speed of the trains; therefore, (within reasonable limits), the slower the speeds the less will be the expenses, when considered with reference to a given amount of business done.
10. The safest and most profitable rate of speed is twenty miles per hour for passenger, and ten miles per hour for freight trains; and they should never exceed these limits, except in cases of emergency.

One of the greatest sources of difficulty and embarrassment in the construction and management of railroads, has been the loose and imperfect manner in which the construction and transportation accounts have been kept; and it is within but a few years that some of our most important railroad companies have seen the importance of adopting such a system as would enable both themselves and others to profit by their experience.

_Retrieved from 'Report of the State Engineer and Surveyor on the Rail Roads of the State of New York for the Fiscal Year ending September 30th, 1857', S. Seymour, Transmitted to the Assembly, March 5, 1858. Albany: C. van Benthuysen, printer to the legislature, No. 407 Broadway_
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List of Acronyms

AAR: Association of American Railroads
CM: Condition Monitoring
CWR: Continuously Welded Rail
DF: Direct Fastening
DSS: Decision Support System
DUT: Delft University of Technology (in the ‘References’ section)
EPC: Engineering, Procurement and Construction Company
ERP: Enterprise Resource Planning (system)
ERS: Embedded Rails System
EU: European Union
FMEA: Failure Modes and Effects Analysis
GDR: Group Decision Room
HSL: High-Speed Line (Project Organisation),
also referring to the Dutch HSL South in Chapters 5 and 7
IM/IP: Infrastructure Manager/Infrastructure Provider
IT/ICT: Information and Communication Technology
ITC: Invitation to Consult
ITT: Invitation to Tender
JR: Japan Railway (company)
LCC: Life-Cycle Costing
LCCP: LifeCycleCostPlan
LCM(+): Life-Cycle Management (Plus)
M&R(-Co): Maintenance and Renewal (Company)
NAD: Non-Available Day
NP46: Dutch rail profile, also known as 46E3, 46 kilograms per metre
NS: Netherlands Railways (in Dutch: Nederlandse Spoorwegen)
OPC: Output Process Contracts (contracts for maintenance and failure repair)
PPC: Production Planning Cycle
PPR: Performance Payment Regime
PS: Power Supply (systems)
PSM: Performance Simulation Model
R&D: Research and Development
RAMS(HE): Reliability, Availability, Maintainability, Safety,
(Health and Environmental Friendliness)
RCM: Reliability Centred Maintenance
RTTI: Railway Technical Research Institute, Japan
SA: System Availability, referring to the second case study
TOC: Transport Operating Company
TR: Track Renewal, also referring to the third case study
TRF: Track Renewal Forecast
TS: Track Selection, referring to the first case study
UIC: International Union of Railways
UIC54: UIC rail profile, 54 kilograms per metre
VE: Value Engineering
1. Introduction

Ideas on 'how to manage rail infrastructure' have changed rapidly over the past two decades. Worldwide, railway sectors faced (or face) reforms, leading to an increased demand for 'professional infrastructure management'. This means that infrastructure should be constructed and maintained to guarantee defined performance levels, e.g. availability, reliability and safety, for lower costs of ownership (affordability). Designers and maintainers are therefore confronted with new, highly challenging questions, such as: How can infrastructure be designed and maintained according to specified performance levels? How can costs of ownership be minimised without harming the vitality of the rail networks in the longer term? How can budget levels for construction and maintenance be justified?

This study is an attempt to assist rail infrastructure managers to answer these questions in a systematic and theoretically founded way through the support of contemporary decision-making processes. This first chapter formulates a problem statement and a number of research questions. Firstly, Section 1 provides a background of the changes that have taken place in the world of railways; this background will be further elaborated in the next chapter. Subsequently, Section 2 introduces the research objective resulting from this background, and Section 3 discusses the research questions and strategies. Finally, Section 4 summarises the research demarcation and provides a chapter outline.

1.1 Background: A switch in railway policy in the 1980s and 1990s

Although most railways started out as private initiatives in the 19th century, public bodies gradually took over operations in most countries or developed detailed regulations for the privately operated railway companies. After the Second World War, nationalised railway companies throughout Europe took care of all the processes needed for rail transport, while governments acted, in fact, as the consumers of railway services. Railways were often too capital-intensive for private companies to operate profitably, especially as other surface and air transport modes rapidly gained market share. However, railways were deemed a valuable asset to society, similar to other publicly owned infrastructures and utilities, such as telecommunications, mail delivery, waste collection, water and energy supply. During the 1960s and 1970s this was considered a natural reason for locating economic ownership in public hands and compensating for operational losses. The European Union even had an official
directive for compensating railways for supplying public services [EU, 1969]; the directive did not specify allowable levels of compensation.

Railways clearly differed from other transport sectors, such as waterways and roads, because operations and infrastructure, i.e. the fixed installations that enable traffic movements, were in the hands of a single body. Apart from the aforementioned macroeconomic standpoint, it had become clear that intensive coordination in construction and operations was needed in order to provide integrated timetables and transparent, payable fare structures. One of the main reasons is that rail infrastructure is not as flexible as other transport modes, as Thompson and Stephan [1998] explain:

'Rail infrastructure which uses more than a small percentage of its capacity requires central control in order to ensure safety and efficiency. Individual users cannot cruise at will. Also, the engineering interaction between steel wheel and steel rails is not simple'.

Within the monolithic railway companies of the 20th century, the Operations Division was responsible for timetabling, ticketing, train and personnel scheduling, traffic control and train maintenance, both for freight and passenger services. The Infrastructure Division was responsible for planning, design, construction and maintenance of all infrastructural subsystems. Infrastructure management took place in hierarchical, centralistic organisations, in which operational, implicit decisions, craftsmanship and the use of historic, technical prescriptions prevailed. There were many people involved in the 'decision-making chain', with technically skilled chiefs in the headquarters making the final decisions for their subsystem [see Swier and Vollenhoven, 1998]. Yet, despite the hierarchy, informal networks played an important role in the correct functioning of the system of 'implicit decision-making' [Swier and Vollenhoven, 1998]. Coordination between infrastructure maintenance and train operations took place in regular cross-disciplinary meetings, while the railway often owned one or more contractors for construction and renewal work.

Although availability and public accessibility of the railways as a 'public asset' was guaranteed as such, the railways' efficiency and customer orientation was increasingly the subject of debate in the 1960s and 1970s. They rapidly lost market share to road and air and their annual losses increased. Over time, their production factors, such as labour conditions, timetables and fare structures, became entirely regulated by governments [Van Twist and Veeneman, 1995; Cantos and Maudos, 2001]. East Japan Railway Culture Foundation described it as [EJRCF, 1998, pp.10-11]:

'The Japanese National Railway's budget was so strictly controlled by the Parliament and the Government that the management could not even determine wages (...). Obtaining a clear understanding of actual management conditions by region or division was difficult [for JNR]. Cross-subsidisation made fostering cost awareness and profit targets in each region and business sector difficult'.

The European Commission reflected on the situation as follows [EU, 1996]:

'In fact railways have been largely insulated from market forces. Governments have a certain responsibility in that they often did not allow
sufficient managerial independence and imposed obligations without compensating fully for the costs involved; they also failed to set clear financial objectives but subsidised losses or let debt pile up'.

Solutions for revitalising the railways were implemented worldwide during the 1980s and 1990s, mostly aiming at privatisation of the entire railway system or parts of it. The governments of the United States and Japan were the first to act. At the end of the 1970s, many North American railways, which had been under private management, were practically bankrupt. The Federal Government took over the management temporarily in order to restructure them; e.g. the Staggers Act resulted in measures of market concentration and deregulation [Sontegaard, 2003]. Amtrak was established as the single, subsidised passenger railway company, while a few dedicated large ‘Class I’ railways each owned a cross-country network for freight transport. As a result, the Class I railways gained a strong impetus to improve their cost structure and customer orientation, except for those areas with captive users [Sontegaard, 2003]. This has led to remarkable results in a short timespan; e.g. Shoener [1994] mentions that Union Pacific reduced their ‘cost of quality’, including impacts of preventive and corrective maintenance, from 30% to 19% of sales within seven years, as measured in 1993. The freight railways maintained market share at 40%.

In Japan, so-called horizontal separation and privatisation was the approach taken for JNR [EJRF, 1995]. Six new Japan Railway (JR) Passenger Companies emerged, which owned parts of the former network, while a national freight company, JR Freight, was allowed to operate services across the new regional networks. The Japan Railway Construction Public Corporation (JRCC) remained the public body for construction of new railway lines, while the government also kept subsidising a number of regional lines and kept part of the shares of the JR companies [Okano, 1994; Van de Velde, 2000]. The JR companies were able to maintain a market share of 21%, while fundamentally improving their cost structure. Because a number of other private passenger companies have a market share of 14%, the total market share for rail amounts to 35%, which contrasts strongly with Europe (market shares of 6-10%) and the USA (market share of 1%) [Okano, 1994].

In the 1990s, the Member States of the European Union accepted EU Directive 91/440, which was the first in a policy of vertical separation of infrastructure and operations [EU, 1991; EU, 1996; EU, 2001; EU, 2002]. Infrastructure had to be transferred to an independent, government-commissioned infrastructure body, further referred to as infrastructure manager (IM). This would, in a next step, enable opening up of the railway market for new operators under non-discriminatory regimes. This policy was initiated with several intentions. Firstly, it would allow transparent cost accounting and decentralised public interference. Secondly, the separation would stimulate efficiency and market performance of the railways. Thirdly, the separation would allow governments to develop a ‘level playing field’ between rail and other transport modes, for example through the internalisation of external costs (e.g. costs of traffic accidents and environmental pollution); separation allows differentiated regimes for investment or user charging between rail, road and air. An

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1 Thompson [1997] mentions the US Freight Railways as an early example of ‘natural’ infrastructure separation: these railways negotiated themselves trackage rights for the use of each other’s networks for defined charges. Also JR Freight and the passenger railways of North America, Amtrak and VIA Rail (Canada), are examples of separated operators, as they own hardly any infrastructure.
important motive was a new belief in the potential role of railways in combating traffic congestion, accidents and environmental pollution. Transparency in cost accounting should stimulate new investments in rail infrastructure, which were lagging behind according to the EU [EU, 1996]:

'Although major investments have been made in recent years and others are planned, there was little attempt to improve railway infrastructure as the motorway networks were built; this helped worsen the imbalance between modes'.

The introduction of vertical separation is still in a transitional stage in many Member States; the reforms in Sweden and the UK have been most far-reaching so far. The privatisation of British Rail is internationally the best-known reform; British Rail was split into around 100 new bodies, including a set of private transport operating companies (TOCs), which obtained long-term franchise contracts [see Bradshaw, 2001; Mathieu, 2002]. The underlying idea was to subsidise the provision of rail transport, and to gradually reduce the amount of subsidy. There is hardly direct competition on the tracks, but there is competitive tendering of these franchises. The TOCs have to pay infrastructure charges to the IM, which are in principle aimed at full cost recovery. Railtrack was the IM until 2002, but Railtrack was taken back into public hands in 2002 and is now named Network Rail. Nevertheless, both passenger and freight traffic increased remarkably in that period; between 1996 and 2000, the number of passenger kilometres (kms) increased by 5% per year [UIC, 2004, Network Rail/Railtrack, 2001].

Sweden also separated infrastructure and operations as early as 1988, but took a more gradual course. One of the main reasons was to permit road and rail to be placed on an equal investment and pricing basis [Jansson and Cardebring, 1989, cited in: Ferreira, 1997]. Experiences have been fairly positive right from the start. The main criticism in 1988 was that the IM, Banverket, was following 'politically determined funding orders', while SJ believed it should determine which track work was needed and when the work should be carried out [Thompson and Stephan, 1998]. In 1998, Banverket was restructured into two divisions, a purchasing and contractor(s) division, and maintenance contracts have recently been increasingly awarded through tendering [Nystrom and Kumar, 2003]. Rail transport operations have also been tendered, which has led to a strong growth in market share.2

The Swedish approach has been followed, to a varying degree, by other countries in the north of the EU, such as the Netherlands and Finland. The Dutch setting will be used many times in this book as a background, because the author has been directly involved in developments on the Dutch network. In the Netherlands, NS Reizigers, an incumbent of the Netherlands Railways, operates the passenger services on the trunk network under a concession until 2010. A few carriers are now licensed for freight transport and two TOCs supply the regional passenger market in two peripheral areas; more regional lines will be tendered in the future [Ministry of Transport (V&W), 1999]. Government subsidy is provided to NS Reizigers and the other TOCs for the operation of unprofitable regional passenger lines.

2 Over the past 10 years, passenger traffic has increased by 55%, of which 32% over the past five years; growth figures for the regional traffic have been in the order of 50-100% [Ohman, 2003].
ProRail, the infrastructure manager, outsources the ongoing maintenance process to three contractors, and tenders large M&R works publicly. The Netherlands started in the frontline of railway restructuring, but needed a long transition phase of nine years before the new Railway Act was approved by the Upper House in 2003. All parties in the Dutch railway sector reflected jointly on this period as follows [Benuten en Bouwen, 2002]:

‘All parts of the railway sector have tried to optimise their own business process. The performance of the rail transport system as a whole is now at stake as a result. Availability and reliability of all resources, i.e. the infrastructure, the rolling stock, and train personnel, have to be raised’.

Some other countries in Europe are more reluctant to move ahead, because of different viewpoints or problems with the labour unions in the creation of activity-based business units for passenger, freight and infrastructure [Monami, 2000; Link, 2003; Batisse, 2003; Vinck, 2003]. As a consequence, the EU countries all develop their own separation model, with different distributions of tasks and decision power among the new actors. Apart from different management philosophies, chosen structures seem also to depend on other local conditions, such as traffic densities.3

All in all, it can be concluded that European railway reform is still in progress and, as Section 2.2 demonstrates, the effects in terms of costs, performance and market share are not easily understood. In 2003, the European Commission proposed a new, second railway package, including an amendment to Directive 91/440, in order to encourage liberalisation of the international freight market [EU, 2002]. The Eastern European countries that joined the EU in 2004 or are candidates for joining later, are also reforming their railway sectors according to the infrastructure separation model. Their past makes this reform process even more difficult, as observed by Thompson and Stephan [1998]:

‘Unfortunately, with few exceptions, it appears that the railways in these countries began neglecting track and rolling-stock maintenance around 1988 and the problem has snowballed since. So far, falling traffic levels have rescued them from the consequences of failing asset availability and reliability, but they cannot continue on their current track without a sizeable financial disaster (...)’.

Finally, similar railway reforms are also seen in other countries around the world. In Latin America and Africa for example, concession models have been implemented under the guidance of the World Bank [Shaw, 1996; Kessidis and Willig, 1995; Galenson and Thompson, 1993]. Under these models, infrastructure ownership remains in public hands, while the concessionaires perform all operational and management processes for a defined, long period of time. Argentina was the first example in 1990 and was followed by other developing countries [Kogan and Thompson, 1994; Carbajo and Estache; Thompson and Stephan, 1998; Rebelo, 1999].

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3 For instance, the Swedish example of the separate tender of intercity traffic is not considered an option for the Dutch trunk network, because of the highly interwoven mix of urban and intercity services.
1.2 A challenge for infrastructure managers and academics

Although rather different reform models have been adopted, the question of why restructuring was undertaken is not hard to answer. A large-scale revitalisation was considered necessary to change the culture of the railways and to create more transparency in their cost and revenue structures. Drastic improvements in efficiency and effectiveness are considered necessary for the survival of rail in the long term. A study in the Netherlands showed that the main roads realised four times as much passenger transport as the rail network for each euro invested during the 1990s [ProRail/RIB, 2000a]. This outcome represents the situation in many European countries; the International Union of Railways (UIC) stated in 2000 that cost effectiveness, i.e. the ratio of transport performance and total costs, should be raised by a factor 3 to make the railways a more attractive mode of transport [UIC, 2000].

Such a breakthrough is far from the case in Europe, but many changing conditions have, nevertheless, taken place in most European regions over the past ten years (see Section 2.2). First of all, operational conditions on many railway lines are increasingly tight in order to realise more diverse transport services (e.g. light rail and high-speed trains), more trains per hour, longer operating hours and an improved punctuality. Secondly, government regulations imply more and more restrictions related to railway safety, labour safety and noise levels. At the same time, funding for infrastructure now has to be obtained more directly within the political process. Thirdly, new organisational and contractual landscapes are emerging around the restructured railways; ‘service level agreements’ or performance regimes are being introduced for transport operators and infrastructure managers, and they will gradually change the internal organisation of IMs. As an illustration, Swier and Vollenhoven [1998] describe how the Infrastructure Group of NS (Netherlands Railways) was transformed during subsequent reorganisations in the 1990s into the current ‘contract management organisation’. Where technically specialised chiefs were initially appointed to supervise their disciplines in a centralised manner, it was decided to ‘de-specialise’ the management task; technical expertise would be primarily maintained in the four remaining Regions and in a central staff department.

Irrespective of the variety in conditions on different rail networks, practically all described changes add, and will add, to more pressure for the IM to optimise work processes and to manage the interfaces with other actors, such as other government agencies, operators and contractors, through contracts. Demands related to performance improvements will increasingly be formulated in explicit, quantitative service levels. This is not only the case for the vertically separated IMs, but also for the infrastructure groups in privatised, integrated railway companies under the growing influence of shareholders [Roney, 2001].

Under the increasing pressures to improve performance quickly, IMs face an important trap, i.e. to focus on supplying short-term cost and/or performance improvements

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4 ProRail is the Dutch infrastructure manager and officially exists since 2003. It was formed through a ‘merger’ of three task organisations that have been responsible for the Dutch network since 1995. Railinfrabeheer (RIB) is responsible, within ProRail, for network construction and preservation, while Railned and Railverkeersleiding are responsible for capacity management and traffic control [ProRail, 2004]. These will be referred to as ‘ProRail/RIB’, ‘ProRail/Railned’ etc., for references before 2003.
only. There are several causes for this trap. Firstly, despite much research in recent years, many rail deterioration processes are not well enough understood to ‘translate’ them into unambiguous quantitative relationships between investment and M&R decisions and long-term quality effects [Ferreira, 1997; Veit, 2003]; uncertainty in these relationships might result in those effects not being sufficiently appreciated. Secondly, governments and shareholders have a preference for short payback periods on investments and quick performance improvements, which can seriously conflict with the nature of railways and optimal spending patterns. The long lifespans of components and their high installation costs, mean that decisions have a high degree of irreversibility. In addition, the consequences of low initial quality and insufficient preventive maintenance, i.e. high cost levels and low system reliability, often only come to light several years later. After reaching certain degradation levels, backlogs in M&R lead to progressive degradation and, hence, capital destruction. Thirdly, although the IM should be the party capable of incorporating such effects into the decision-making, either implicitly or explicitly, there are many impeding factors. The long-term view on designing and maintaining usually conflicts with organisational and institutional boundaries, such as allocated budgets, standard operating procedures, established relations with other actors, and external regulations. Most of these boundaries have a long history, and decision makers usually consider only incremental changes.

Inertia in the ‘implicit decision-making culture’ and budget allocations are thus closely related and could lead to undesirable outcomes under the changing conditions. It is likely that the phenomena mentioned will result in IMs trying to obtain high levels of funding in order to be sure of meeting performance expectations or, contrarily, IMs masking deferred investments. It is even possible that both over-investment and under-investment coexist in the railway sector, because of misallocation [ECIS, 1996, p. 27 – cited in De Jong, 1998; Van de Velde, 2000]. Van de Velde states that ‘separation can easily lead to inadequate investment incentives and lengthy bureaucratic procedures with over-investment paid for by the taxpayer, while simpler punctual shorter-term investments would be more economical’. Allen [2003] reflects upon a well-known case:

'It is unremarkable that a business should lose control of its costs when it simultaneously enjoys unprecedented access to additional funds, an upsurge in market demand and political patronage should lose control of its costs. If, in addition, the business is confronted with increasingly onerous and perhaps unrealistic restrictions on its working practices and is subjected to several high profile public enquiries, the conditions for a loss of management control are complete. Such was the fate of Railtrack'.

The European Commission also seems to be worried with respect to the functioning of the separated IMs in their changing environment [EU, 1996, p. 19]:

5 Ferreira states that the effect of train speeds, axle-loads, and vehicle types on maintenance effort can currently be estimated with a great deal of precision (p.192).'

6 Rail infrastructure is a highly capital-intensive production asset to construct and maintain, representing (in the EU) 30-45% of the total operating costs [Vandenbroeke, 1994; Profiliidis, 2001].

7 This is not a peculiarity of railways; in a representative survey Vonk and Smit [1996] found that few Dutch companies apply 'zero-base budgeting'; they 'reuse' historical maintenance budgets, which are incrementally changed.
The railway advisory group to Commissioner Kinnock considered that infrastructure costs were too high and that this was one of the factors which had contributed to rail's decline. Infrastructure owners are in monopoly positions vis-à-vis train operators and therefore mechanisms are needed to ensure that they have adequate incentives to improve efficiency and reduce costs. This will become increasingly important as the railways move toward greater separation of infrastructure management and transport operations.

At EU level, emphasis is placed on introducing infrastructure charging principles in order to create incentives of customer orientation and efficiency, since: 'transactions have to be explicit and transparent' [EU, 1996]. Although such incentives may be part of the solution to help infrastructure managers improve their internal processes, this dissertation will directly focus on required changes in internal decision-making processes concerning design and M&R within the IM's organisation.

A major shift in the infrastructure management processes seems necessary. The next chapters argue that a decision-making approach is searched for, in which design and maintenance requirements can be systematically derived from the quantitative performance requirements of other actors (e.g. required capacity, budget and RAMS levels). In fact, this approach stems from the field of 'systems engineering' and proves to be an area that has gained attention in all capital-intensive industries in the last two decades. As Chapter 3 will show, concepts are available nowadays in the literature to support design and maintenance strategies that incorporate such performance impacts.

However, as Chapter 2 will further demonstrate, the introduction of a 'systems' or 'life-cycle' view appears yet hard to realise in the decision-making in the European railway sector. Substantial R&D efforts have been undertaken, but they have been highly fragmented and do not seem to solve the difficulties of IMs in aligning their decision-making processes in a pragmatic sense to the new, high-level performance objectives, such as life-cycle costs, reliability and availability. This was the reason for focusing this research on the issue of how the railway sector (in general) and rail infrastructure managers (in particular) can be assisted in taking the first step in contemporary decision-making towards a systems-engineering-based process. The research objective was therefore formulated as follows.

'To develop and test an approach that can immediately assist the rail infrastructure sector in identifying and adopting design and maintenance strategies, which take 'life-cycle' impacts into account (within required levels of technical and functional performance).'

The research focuses on the design and preservation of the linear infrastructure (i.e. excluding stations), and is believed to have both societal and scientific relevance. Developing such an approach should be beneficial for taxpayers and travellers alike, because it should assist (railway) IMs to make better, more cost-effective decisions. Moreover, it should generate knowledge regarding ways of effective support of IMs, which fits into a broader academic challenge to develop management control principles for capital-intensive production and service systems. Stavenuiter [2002] found that there is a lack of 'structured and applied knowledge about cost-effective management control of capital assets' in general, despite all
maintenance engineering literature currently available. In the case of infrastructure systems, this lack of knowledge is perhaps even more problematic because, similar to railways, a whole range of infrastructure and utility systems have been split up and privatised over the last decade [Twist and Veeneman, 1995]. In many systems, where new IMs, regulators, and private operators have come into existence, there are growing concerns as to whether long-term performance aspects are sufficiently considered (see Chapter 3). Hopefully, findings from this research will therefore provide directions for research and management in other infrastructure systems and utilities as well.

Three connotations have to be made with respect to this objective. Firstly, this research is clearly aimed to help introduce life-cycle-based thinking into the design and maintenance processes. This implies that the study itself is not intended to supply improved technologies, construction and M&R standards, but will hopefully provide insight into ways to assist IMs in this process of innovation. ‘Technical’ outcomes will only be included in this report for the purpose of demonstrating the functioning of the approach in practical applications. Secondly, the approach should be able to ‘work’ under the current conditions; explored ways for decision support should be effective in a context of absent data and maintenance planning systems. Thirdly, note that it is not possible to evaluate the ultimate impacts with regard to realised system performance. This is a general issue in this type of policy analytic studies; the real effects of decisions are difficult to measure and occur over a longer period of time. Apart from the required patience, it becomes difficult to isolate the effects of the analysis over time [Thissen and Twaalffhoven, 2000]. Figure 1.1 visualises this evaluation problem: outcomes will not only depend on the quality of the analysis, but also on other factors. However, it is possible to limit the evaluation to the quality of the direct results and the process itself, which can include a test to see whether life-cycle cost expectations are based on state-of-the-art knowledge. The following section discusses the research questions and strategies deployed to meet the research objective.

![Figure 1.1: Relationship between quality of analysis and performance of the rail system](image)

**1.3 Research questions and strategy**

A number of research questions were formulated to guide the research. These are introduced below, including the starting points and the research strategies used. As a first step, an
analysis of the (changing) conditions in the railway design and maintenance environment was considered necessary input for developing an approach that aims to support real-life decision-making. The following question was therefore formulated:

**Research question 1:** Which changes are occurring in the rail infrastructure sector, and which changes do they lead to in the design and preservation processes?

The investigation focused on the changes in institutional arrangements and actual conditions ‘on the railway track’. A scan of policy documents, annual reports and project-related publications from national governments and rail authorities was made; visits to a number of leading passenger railways were used to better identify their R&D and ‘management change’ programmes (see Appendix A). A view on the state-of-the-art in railway design and preservation was thus developed, which resulted in an identification of the changes and bottlenecks in railway design and maintenance.

The next step in the research was to study the literature for concepts and methods to introduce a ‘systems’ view, in which impacts of decisions on other parts of the system, during the system life-cycle, are well considered. The following question was formulated:

**Research question 2:** How can a life-cycle-based approach to railway design and preservation be stimulated in today’s railway environment, from a theoretical point of view?

The answer was sought in two subsequent steps; this included theoretical expectations on improvements, which should be realised in railway design and M&R processes. The first step was a search through the maintenance engineering literature for concepts and methods that were available for dealing with the identified bottlenecks. Several ‘sources of inspiration’ for introducing a systematic, performance-based approach to design and maintenance were found in the literature. Life-cycle costing (LCC) was expected to be a particularly useful vehicle for introducing ‘systems’ or ‘life-cycle’ thinking, considering the state of the art in the rail sector (see further Chapter 3). LCC is defined as an economic assessment of an item, system, or facility and competing design alternatives considering all significant costs over the economic life, expressed in terms of equivalent currency units [Kirk and Dell’Isola, 1995].

The second step was a search through the literature for public administration and policy analysis. Using LCC, it should be possible to improve the timeliness and quality of the information basis for decision makers, with respect to long-term impacts; however, knowledge should be scientifically sound and helpful for the policy process. Many decision-making processes have a multi-party or ‘multi-actor’ nature, which means that participation by a range of parties with different means, problem perceptions, and often conflicting stakes is needed in order to realise changes in the policy arena. These parties are usually mutually dependent, which means that the policy process itself is as important as the content-related expertise needed to further the decision-making process [Van de Riet, 2003]. This seems particularly the case for restructured infrastructure systems with separated operators, although large, integrated companies, whether privatised or not, also have multi-party elements. For example, Swier [ProRail/RIB, 1995] compared the Dutch railway sector and the Union
Pacific (UP) company and concluded: 'Despite UP being one company, the large geographical distances cause organisational problems, which show similarity to the problems of Netherlands Railways with its separated infrastructure and market organisations'.

The search resulted in the design of a particular LCC-based approach, which was expected to be effective in dynamic, strategic and tactical decision-making. The question remained as to whether the developed 'theory' was correct and worked out well in the railway sector. This question was formulated as follows:

| Research question 3: Is a decision-support approach able to have courses of action developed and adopted, which are expected to be more cost-effective (over the system life-cycle)? |

The third step of this research is therefore to test the approach; this test should provide insight into the effectiveness of the approach in both improving the process and the quality of the resulting decisions in terms of life-cycle performance. Improving the process is an important means to improve commitment among important stakeholders. Answering this question could provide new insights into the opportunities and obstacles for a life-cycle approach and into the applicability of the LCC concept.

The first issue to be dealt with was the research method used to answer this question. An important observation is that the approach is designed for contemporary processes, which cannot be considered isolated from their organisational and societal context. Many factors have an impact on the perceptions and actions of the participants and few research methods are therefore useful. For instance, a survey can provide data on the opinions of practitioners, but cannot reveal the actual performance of the approach; it would result in rather hypothetical findings.

A serious option was to test the approach in a controlled setting, i.e. in a gaming. Gamings are in fact simulated decision-making processes. They are organised in computer-supported environments, which simulate the outside environment; a game-play mimics the actor interactions [Geurts and Vennix, 1989; Mayer and Veeneman, 2003]. The computer software and the human assistants can register events and behaviour of the participants, which are usually practitioners from the field. An advantage of such a setting is that the process can be played several times with the same participants and under pre-set conditions; it can be completed much faster than in real life, which makes it possible to study the final impacts of decisions within the context of the gaming. Veeneman [2002] describes, for example, a two-day gaming of a tender and management process for public metropolitan transport, which would take several years in reality.

It is generally recommended to use gaming only for research purposes when a real-life test cannot be organised (e.g. for obtaining a first insight into possible impacts of proposed governmental policies; see Veeneman, 2002). Developing such a gaming requires

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8 Swier found that the use of information systems helped UP overcome these problems to a large degree; the effort needed was, however, immense [ProRail/RIB, 1995, p.5]. UP's vision states that data needs to be available, accessible and easy to comprehend, because: 'only then is it possible that the average employee derives power from the data, which is crucial for a 'flatter' organisation.'
considerable investigation and resources. An important issue is how well reality is reflected in the gaming. Firstly, an abstract model has to be made to represent the complex reality in a modelled environment. Secondly, there is always the risk that participants behave differently in such a low-risk environment than in real life, where they have to 'live' within a larger organisation with more interactions and with real consequences. It was therefore decided to use gaming as an option of last resort, and to look actively, but selectively, for real-life case studies in the Dutch rail sector.

The search for suitable case studies ended in one case study being cancelled at an early stage and three case studies being completed. The case study that was cancelled concerned a decision-making process in a tender to construct a small part of the Betuwelijn, a dedicated freight line that will link the Rotterdam harbour with the German hinterland. The study would have been performed alongside one of the bidding consortia and was selected, since the procuring agency, ProRail/RIB, initially required to include a 10-year maintenance period. The reason for ending the study was the elimination of that requirement. The three completed case studies concerned:

1. An assessment of track designs for the new Dutch high-speed line, HSL South, organised within an international consortium during the consultation phase.
2. An analysis of design and maintenance choices in order to improve the overall performance of the HSL South rail system during the tendering phase.
3. A revision of existing track renewal practices for the Dutch conventional network, organised within ProRail/RIB.

The author chose to explore the usability of the research approach for both new railway construction and for maintenance of existing rail networks. It was hoped that this would contribute to a ‘rich picture’ of the usability of the approach. The premise to be tested was that the decision support provided actually improves the quality of the decision-making process and its outcomes; it was clear from the start that performing this test would be an important challenge for the researcher. Case study research is not comparable to experimenting in a laboratory setting; the main drawbacks are that the researcher has little control over events; the ‘experiment’ cannot be replicated under exactly the same conditions; and the boundaries between phenomenon and context not being clearly evident [Yin, 1989]. In spite of many data sources being available for finding and interpreting the course of the decision-making process (e.g. documents, archive records, interviews, observations and artefacts, such as computer tools), results of actions are not easily measurable and understood. They need to be derived from changes in the stated policy, the number of alternative solutions actually considered in the decision-making process etc. Handbooks such as Yin [1989] were used to set up the case study research.

The ‘action research’ approach, in which the author would be both participant and observer, best fitted the ‘how to’, explorative character of this research [Dick, 1993]. An evaluation protocol was designed in advance to guarantee a traceable, objective research process; the precise manner of dealing with it in (evaluating) the case studies is discussed in Section 4.4. It was decided to base the evaluation of the supporting approach on the stated opinions of stakeholders and official documents, in order to avoid a biased picture based on the author’s personal notes. Anonymous interviews were held with all participants between
two and five months after each study (see Appendix A for the list of interviewees and Appendix B for the questions); at that point in time, the interviewees were considered to have adequate insight into the results of the decision support provided. Each interviewee had the opportunity to propose corrections to the written report immediately after the interview. The evaluation, discussed in Chapter 7, has been limited to the validity and credibility of the decision support and its direct results, in terms of the quality of the decision-making process, expected life-cycle cost improvements and stated commitment to the outcomes. For certain indicators, these perceptions may not represent the ‘real’ effectiveness due to biases in the reasoning of interviewees (e.g. unjustified optimism or pessimism); case study descriptions on the basis of official minutes of meetings and project reports provided a means to verify some of the perceptions (see further Section 4.4 and Chapter 7). The following section briefly summarises the research focus and demarcation. It also provides an outline of Chapters 2-8, which document the research.

1.4 Summary and chapter outline

The policy and operational environment of the railway sector has changed considerably over the last two decades, which has resulted in the challenge to reduce the costs of rail transport drastically, while accommodating larger traffic volumes. The changed expectations of policymakers (and the public) cause a risk, i.e. that infrastructure managers opt for short-term success only, resulting in disproportionate budget claims or negative impacts in the long term. This risk is caused by the fact that railway design and maintenance processes have never been set up to analyse and demonstrate effectiveness of railway designs and maintenance and renewal (M&R) programmes in terms of quantified levels of reliability, availability, affordability, etc. Possibly, the implicit aims of infrastructure construction and maintenance staff were already trying to supply a reliable rail network for a ‘fair’ cost of ownership, but, in the current environment, it is feared that such an ‘implicit approach’ is not sufficient. This research was therefore set up to identify methods that can immediately improve the quality of decision-making.

The objective is to develop, in a number of steps, a decision-support approach that generates timely data on system-wide, long-term effects of individual decisions and to test and indicate its effectiveness in the decision-making process. The approach is based on concepts and ideas from the fields of industrial engineering and policy science. It will particularly be set up from a ‘policy analytic’ viewpoint, in which it is assumed that the provision of timely data on future decision impacts, as well as the participation of stakeholders in the analysis, can improve the decision-making process and the resulting decisions [see Van de Riet, 2003]. The research objective implies that the research has an explorative nature that focuses on developing and testing the effects of decision support on tactical and strategic decision-making processes for railway design and maintenance. Consequently, less attention is paid to prescriptive, detailed models, concerning the question how to organise ‘life-cycle management’ or ‘asset management’ in the rail sector, and to supplying technical knowledge (e.g. degradation models) and detailed cost data.
Research questions will be answered one by one in the following chapters (see Figure 1.2). Chapter 2 identifies global trends in the conditions for railway design and maintenance as well as the responses of the IMs. Changing management needs are thus identified. Chapter 3 explores the industrial (maintenance) engineering literature in order to identify its possible contributions. Chapter 4 presents a supporting approach, which should be able to immediately stimulate life-cycle-based decision-making. Next, the course of three case studies is described in Chapters 5 and 6. Chapter 7 evaluates the results achieved by this approach in these case studies. Chapter 8 ends with conclusions and recommendations for further research and for the railway sector as a whole. The ‘Conclusion’ sections of Chapters 2, 3, 4 and 7 answer the three research questions concisely, while Section 8.1 also summarises the main findings.

Figure 1.2: Research and chapter outline
2. Railway Construction and Preservation

This chapter answers the first research question: Which changes are occurring in the rail infrastructure sector, and which changes do they lead to in design and preservation processes? Firstly, Section 1 introduces the task of infrastructure management, sometimes referred to as 'infrastructure provision', in the context of the entire rail transport system. Subsequently, Section 2 identifies key trends in conditions and requirements for infrastructure managers (IMs). Section 3 identifies typical 'responses' of IMs and their suppliers in terms of changes to management processes and R&D programmes. Section 4 reflects on the changes found and their implications.

2.1 A conceptual model of the rail transport sector

Where integrated railways once operated in practically all countries around the world, the picture today is considerably more varied; as a result, interfaces in the system that were blurred in the days of the monolithic state railway have become fully visible. This section presents the rail transport system in a generic model, consisting of several layers and interfaces. With this model, depicted in Figure 2.1, it is possible to describe any rail transport system. It assists in analysing the position of IMs in different rail sectors, irrespective of whether they are still part of an integrated railway or are separated. Schaafsma [2001] has elaborated the model in more detail.

The model depicted in Figure 2.1 (on the next page) distinguishes different service levels in the rail transport system. Each of the lower-level services enables processes that take place at a higher level, and higher-level processes therefore place specific requirements on the lower-level processes. An example is rail freight having other infrastructure design and maintenance needs than passenger traffic (axle-loads, radii, signalling block distances, the availability and reliability levels required etc.). Each of the service layers uses resources of its own (e.g. train personnel) or uses services at a lower level (e.g. leased locomotives and train-sets) to perform its required functions (e.g. running a train). A more or lesser-developed ‘market’ exists between each of these levels, i.e., different products are available with different price and quality levels. Governments, IMs and TOCs are intervening in this market in order to match supply and demand, while special, regulating bodies try to control crucial market aspects (e.g. safety standards, market access and transparency etc.).
The existence of a 'transport needs market' initiates all processes. This market consists of persons who participate in economic and social activities, and shippers supplying goods to be transported. Passengers and goods enter and leave the rail transport market through stations and freight collection points, where TOCs offer their services, according to specified frequencies, travel fares, levels of punctuality etc.

The TOCs have to perform different tasks for the provision of transport services, such as splitting and bundling of traffic services (e.g. changing trains or coupling train-sets), protecting both people and goods, and providing information to customers. In some cases logistic service providers can function as intermediaries between the end users and the TOCs: they manage the logistic chain for the customers. Legislation can be used to define and control the quality of service; an example is a refund scheme for delays.

Providing connections requires physical movement of the trains. Traffic functions include the carrying, guiding, driving and propelling of trains as well as providing a safe moving space (train paths or slots). The most important traffic means are infrastructure and rolling stock, i.e. trains and locomotives, plus train and traffic control personnel. A market can exist for each of these resources, although train personnel are usually trained and pooled within the TOCs. Rolling stock leasing companies (ROSCOs) can provide traction and vehicles for a specific lease price and reliability. The IM, commissioned by the infrastructure owner(s), provides train slots with a specific functionality and reliability for a specific user charge; in order to do so, the IM needs to plan network capacity (train frequencies) and
guarantee functionality and quality of the infrastructure. When the current infrastructure capacity is insufficient for traffic needs, which are deemed valuable or profitable, the network can be extended or existing lines can be upgraded in terms of alignment, switch designs, axle loads, station platform height, or traction systems. Requirements to the infrastructure basically come down to the following:

1. The infrastructure has to support and guide the trains, while minimising the impact on the environment. A track structure is needed to distribute the loads of the trains over the supporting earth bed or civil substructure and to avoid derailments. Its design must therefore suit a specific environment. For example, high-speed traffic requires straighter alignment and stronger noise abatement properties.

2. The infrastructure must feed the traction of electric locomotives and train-sets. Power needs to be collected and distributed through substations to the catenary.

3. The infrastructure must protect and control the train traffic. Central traffic control of the train movements is usually required to guide the trains through the network; command, control and communication (CCC) systems provide the equipment needed for traffic control. Signals and level-crossing protection equipment are used to regulate the safe moving space of each train, and automatic train protection (ATP) will bring trains to a halt when passing a signal at danger. Finally, auxiliary safety equipment is needed in tunnels (e.g. sprinkler systems and escape routes).

4. The infrastructure has to enable the loading and unloading in the rail transport system. Passengers, freight and trains enter and leave the system through stations, terminals and feeder lines. Facilities such as station platforms, walkways, travel information displays and shunting or marshalling yards are needed to transfer passengers and freight to other service routes.

Apart from allocating slots (train paths and maintenance works), the IM should pay considerable attention to the physical interfaces with the operating side since even small deviations lead to unsafe traffic conditions or cause quality deterioration. Two important interfaces that need constant attention, are wheel-rail and pantograph-catenary; in both cases, most problems have a mechanical nature [Lipscomb Smith, 2000], and ‘the poor condition of one half of the interface can directly cause significant exceptional costs to be incurred by the other’ [Fry, 1999]. As an example, ‘inadequate performance of track lubrication equipment can cause excessive flange wear and a dramatic increase in wheel set maintenance costs’ [Fry, 1999]. Lipscomb Smith [2000] mentions that both interfaces can heavily interrelate with each other under increasing operating speeds:

‘Pantographs are placed over the body centre-line in order to ensure that they follow a path as near as possible coincident with the track centre-line. However, from this position the pantograph is subject to the greatest dynamic inputs from the interaction (...) with the track. Keeping the pantograph trajectory as level as possible will benefit both the catenary system and the pantograph’.

The complexity and importance of the interfaces is reflected in the fact that most engineering research is directly related to these interfaces; examples are research into Rolling
Contact Fatigue [see Smulders and Hiensch, 2003], preventive grinding strategies [see Burlington Northern Santa Fe, 1999], and track-friendly vehicle designs [see Frohling, 1999].

The IM undertakes regular routine inspections, maintenance and renewal works in order to ensure that infrastructure quality remains within defined standards. The railway track system can serve as an example. First of all, there are many types of railway track available today, ranging from traditional tracks in ballast (crushed stone) to tracks with concrete beds, which require rather different inspection and maintenance programmes. In the case of concrete or slab track, the initial geometric quality is of utmost importance; if it is constructed well, geometric maintenance is hardly necessary. In the case of a ballasted track, initial quality is also important, but will not avoid the need for geometric maintenance, as ballasted track is not a fixed structure. Regular levelling and lining (tamping) will be necessary to retain horizontal and vertical alignment (e.g. the cant applied in curves) within certain limits. Apart from geometry, periodic overhaul and renewal of the components, i.e. ballast, sleepers, rails, fastenings (connecting devices between rails and sleepers), and rubber pads (supporting devices for the rails), are necessary to guarantee a sufficient structural quality. Finally, the rail surface profile itself should be well maintained through lubrication and grinding. In order to plan maintenance timely, inspections are held using patrol walks and periodic ‘campaigns’ by track recording coach (TRC).

Special regulatory bodies, often appointed to monitor traffic safety, can develop standards for the quality of the technical interfaces (infrastructure and rolling-stock quality). Clementson [2001] discusses a number of examples from the UK: the Rail Safety and Standards Board; Wheel/Rail Interface System Authority (WRISA) and the Train Protection and Warning System, System Authority (TPWSSA).

Apart from a certain amount of maintenance slots or possessions, the IM needs budgets, machines, materials and labour to perform its tasks. Required resources and expertise for designing and maintaining the assets will be looked for in-house or in the infrastructure supply market. The supply market generally consists of contractors that offer heavy equipment for major overhaul and renewal, but in a number of cases, such as the UK (until 2004) and the Netherlands, contractors carry out most of the maintenance and repair process. In that case, these contractors or ‘infrastructure maintenance companies’ (IMCs) may not only deliver a product (e.g. a renewed track), but a service (e.g. a mean time between failure); in special cases, they can even pre-finance construction or upgrading works.

As discussed above, processes are at work at every level in the rail transport system to realise the functions of that level in compliance with quality and performance requirements, which were, ideally, agreed upon with the other levels. These processes can usually be distinguished in strategic, tactical and operational decision-making. Strategic decisions have long-term impacts on the entire system; examples are the planning of track layout and initial quality and preventative maintenance strategies to be deployed. These decisions directly determine available transport capacity, reliability, maintainability and economic lifespans. Tactical decisions have an impact on the medium term, such as the allocation of slots to specific TOCs and the timing of periodic M&R works. Operational decisions, such as traffic control interventions and logistic decisions in the implementation of M&R, have short-term impacts. Figure 2.2 combines the aforementioned functions and processes in a single picture.
As previously mentioned, this research focuses on the 'linear rail infrastructure' and not the 'nodes', i.e. stations and terminals. Apart from the railway track, the linear railway assets consist of power supply and command, control and communication (CCC) systems. Many performance problems are related to the linear assets, which are subject to (rail-bound) traffic. The following section describes today's conditions for IMs and trends in the conditions based on a study of developments in the rail sector. Indicated changes do not occur on every network or country with the same intensity.

2.2 Today's conditions for infrastructure management

Railway systems, transport demands and society as a whole are subject to change. Key trends in these three areas are indicated in the subsections below.

2.2.1 Institutional setting

Chapter 1 has already made it clear that railways faced drastic reforms on a global scale. Three basic railway models are currently found, with many more variations. Firstly, there are
countries that still have integrated, state-owned railways. Secondly, there are countries with integrated, private railways, providing transport on their own infrastructure or through infrastructure ‘owned’ for a defined time period (Build, Operate, and Transfer concessions). Thirdly, there are countries where the management of infrastructure and operations are (being) separated.

These different models will probably have important impacts on the incentives and objectives of the infrastructure staff but, as suggested in Chapter 1, these are difficult to reveal due to their implicit nature. A UIC study found that the North American Class I railways have much lower infrastructure costs, compared to Europe, which can only be partly explained by lower track quality and traffic conditions [UIC, 2002; Stalder, 2003]. Adopting a new model will therefore probably lead to changing incentives in the body managing the infrastructure.

First of all, throughout Europe, compatibility of national rail networks to European standards (so-called interoperability) has been a factor requiring increasing management attention since the 1990s. Historical boundaries on the European network hinder a well-functioning European market, e.g. each country develops its own regulations and systems for signalling and power supply. For example, international high-speed passenger trains need to have many signalling antennae and traction types on board, while the envisioned European ‘freight freeways’ are hindered by national safety legislation and priorities in slot allocation [Van Ham and Naar, 1998]. EU Directives 96/48 and 2001/16 impose design requirements on the Member States that should lead to a single, interoperable railway system.

Secondly, although many governments have so far refrained from competition, the rail sector is increasingly seeing more formal, business-like performance regimes being introduced, because responsibilities for subsystems are distributed over an increasing number of parties. Figure 2.3 on the next page shows the contractual landscape that emerged in the rail sector of the UK in the 1990s and which is likely to emerge, to a less drastic degree, in other countries. Studies are currently being carried out in the Netherlands into developing a performance regime for ProRail, coupled to a rise in infrastructure charges to be paid. ProRail currently shares 50% of the costs (of refunding tickets to passengers) incurred by NS Reizigers. Reimbursements are made when delays last longer than 30 minutes, and the infrastructure causes around 50% of such long delays.10 The ultimate goal of the performance regime to be introduced is to differentiate between different transport corridors, however a flat performance and infrastructure-charging regime is expected first [Den Buurman, 2001].

Thirdly, governments still largely subsidise the European rail system, which has consequences for budgetary processes and performance incentives in the new IMs. Government funding is received either via subsidies to TOCs or via budgets for infrastructure M&R. For example, in the 1990s Railtrack was expected to ‘live’ as a privatised IM on user charges, paid by the TOCs [Brading, 2000]; the government paid for the franchise contracts of the TOCs. In the Netherlands, the government subsidises the sector mainly via ProRail funding and via contracts with NS for transport on so-called ‘non-profitable lines’. The Ministry of Finance is the NS shareholder, while the Ministry of Transport is responsible for railway policy.

9 The word ‘signalling’ is used throughout the remaining text, rather than CCC.
10 Information supplied by Gerlof den Buurman.
Figure 2.3: Possible contractual landscape in a vertically separated rail sector

The separation of infrastructure management in the Netherlands has had a profound effect on the funding of infrastructure maintenance, because ProRail has to obtain an important part of its budget directly from the political process. A first effect has been that the Track Renewal (TR) budget is now treated as cash (fond perdu) funding: budget obtained must be spent in the designated year. This is in contrast to previous arrangements, where TR was remunerated from a special NS fund that was topped up annually [NS, 1988]; there was only an indirect coupling with the political process and it was not required to use the budget entirely in a designated year. This change may have urged regional staff to pay more attention to usage of available funding, rather than a more thorough investigation of track M&R needs [ProRail, 2003a].\textsuperscript{11} A second effect has been that budget levels have become less stable. At the end of the 1990s, government funding of M&R was rapidly reduced, as agreed upon in 1995 after the first step in restructuring the former NS [Wijffels et al., 1992; Netherlands Court of Audit, 1999].\textsuperscript{12} Since the contracts for small maintenance had also become more expensive, this situation resulted, in the end, in strong budget reductions for renewals (in 1999).\textsuperscript{13} A report of ProRail/RIB, stating the need for more TR, ended the situation [ProRail/RIB, 1999a]. Nevertheless, the Netherlands Court of Audit concluded that haste should be made in developing a costing regime for M&R, as such a regime was unavailable.\textsuperscript{14}

\textsuperscript{11} In the other technical systems, depreciation of historical acquisition costs is used.

\textsuperscript{12} Railinfrabeheer, now ProRail, was able to attract loans from the private capital market and in 1997 had a total debt of more than 1.5 billion euros; at first the Ministry of Transport remunerated the interest on these loans fully, but from 1997 to 2001 this contribution was reduced to zero.

\textsuperscript{13} Causes for the increase in small maintenance costs were found in the outsourcing of maintenance, the inflation of labour costs, limitation of maintenance slots, and, most of all, the new labour safety policy; this policy alone was responsible for a 10% cost increase between 1994 and 2000 [ProRail/RIB, 2001].

\textsuperscript{14} Although a one-to-one comparison would need considerable investigation, similar problems between IM and government probably occur in other countries. It is, at least, remarkable that many IMs recently reported facing
Unavailability of a costing framework makes the preservation of infrastructure vulnerable to a well-known tendency in political processes to focus on isolated, high-profile projects with high expenditure of efforts and resources [Wittwer et al., 2002; European Centre for Infrastructural Studies, 1996]. This can have two profound effects. Firstly, it causes undesirable fluctuations in maintenance budgets for existing infrastructure, since infrastructure funds can only be used once. Budget variations lead to ‘feast or famine’ situations that bring associated inefficiencies [TRB, 2002], e.g. it can result in irregular patterns in track possession claims and resources, which lead to planning problems and high supplier prices in peak times. When investments lag behind, the consequence can be that too much money is put into maintenance of weak spots. Veit [2000] describes how one of the ways deployed for a structural reduction of the overall M&R expenditure on the Austrian rail network was made through the one-time renewal of spots with permanent speed restrictions. Secondly, it can lead to choices that limit the functionality of railway lines or which result in more future maintenance [Netherlands Court of Audit, 2000, p. 99; Van der Mooren, 1987].

Privatised railways are also not free from a kind of ‘shareholder dynamism’. Roney [2001] mentions the stock price as being a key driver of top management behaviour. Stock analysts reward the railway company with a ‘buy’, if it can supply continuous growth in operating income; ‘this is important for raising capital and is profitable for management as well’. Roney [2001] adds:

‘Shareholders are amazingly fickle. They want their returns now. This puts lots of focus on the next quarter, and correspondingly less focus on the 5-year and 10-year plan. (...) Most technological advances are capital-intensive. In the short term, improving asset velocity, shedding locomotives and adding additional tonnage behind the units obtain the best results. But what next?’

Finally, a trend that can recently be recognised in the construction or upgrading of railway lines is the involvement of private partners, through private finance initiatives and public-private partnerships (PPP). This involvement has two main motives: a belief that the private sector can perform more efficiently than the public sector and that the private sector represents a new source of funding [Hakim, 1996, p. 5]. This construction will have a profound effect on the organisation of the sector and decision-making processes, wherever it is applied. Instead of tendering construction works in small portions using detailed specifications to traditional contractors, international consortia (contractors, material suppliers, engineering consultants and banks) will now participate in the tendering. The focus in the process will be on high-level objectives (e.g. transport levels to be accommodated) and financing schemes. An early example of such private involvement is Eurotunnel, which constructed the 50-km-long Channel Tunnel between the UK and France, and obtained a concession to operate the tunnel until 2086 [Eurotunnel, 2004]. Other recent examples include:

important cutbacks in renewals as well as having M&R backlogs – e.g. see [Railtrack, 2000; Modern Railways, May 2003; Niemimukko, 2003; Bylund, 2003].

15 Okano [1994] mentions examples from Japan; he describes how regional communities in Japan lobby for the construction of new Shinkansen lines to their region, while the JR companies are protesting because they are not foreseeing a profitable exploitation of these lines.
- the construction of the Taiwanese high-speed line, which is a Build, Operate, and Transfer (BOT) contract with a time horizon of 35 years, comprising 345 kilometres of line, 10 stations and areas for real-estate development [Chen, 2000];
- the London Underground PPP, where all assets (including stations and trains) have been transferred into three so-called ‘Infracos’ contracts for a period of 30 years. Two consortia obtained these contracts; they will realise investments amounting to several billions of pounds for improving the quality of the infrastructure [London Transport, 2004];
- the Infrastructure Provider Contract for constructing and managing the Dutch HSL South rail system over a length of around 100 km. This contract has a total value of almost €3 billion and a time horizon of 30 years [Zoeteman and De Weis, 2003]. It will be discussed extensively in Chapter 5.

Examples of private sector company involvement in the maintenance of heavy rail networks are (still) less drastic. Some IMs, such as ProRail, started to use outsourcing (see Section 2.3.1) and Design and Construct contracts, in which contractors (of renewals) also take responsibility for the engineering process.

2.2.2 Rail transport concepts

It is not only the institutions that are changing, but also the operating environment. New transport concepts are being introduced in several countries in order to serve market demands better; these include container shuttle trains, heavy haul transport, high-speed trains and ‘light rail’.\(^{16}\) Developments in the transport environments are, however, rather diffuse on a global or even European scale. As previously mentioned in Chapter 1, the North American freight railways and the Japanese passenger railways maintained their market share; in other words, their transport volumes have steadily grown over the last two decades. In Europe the market share for rail is generally small, in the order of 6-10% for passenger traffic, with Switzerland being a positive exception [Carron, 2004]. Nevertheless, moderate or even strong growth has been realised in a range of EU Member States, also including unreformed railways such as the Belgian SNCF/NMBS. Because of massive investments, growth has been particularly strong in the high-speed passenger segment (see Figures 2.4 and 2.5 on the next page), while growth in freight traffic is mainly seen on a number of ‘freight freeways’, e.g. across the Alps, with an overall decreasing market share. Aggregated and detailed data on traffic volumes for various continents are available on the UIC website [UIC, 2004].

Despite the variety, it can be concluded that many IMs face pressures to accommodate more traffic. A first effect is the wish, or demand, for longer operating hours per day on the ‘arteries’ of intensively used rail networks, which undermines the availability of M&R slots. For example, on the main Dutch lines the duration of free nightly M&R slots are usually six hours or less [Tegelberg, 2004]. This will also be the case for the Dutch high-speed line, which is generally intended to use a 24-hour timetable with nightly maintenance slots on one of the two tracks [HSL P.O., 1999]. A final example is the new Korean HSL between Seoul and Pusan, which will have nightly maintenance slots of only four hours, leaving an effective maintenance time of only 2.5 hours [Esveld, 2001].

\(^{16}\) Light-rail vehicles are able to run both on tramway, metro and heavy rail networks.
Notice that the high-speed segment accounts for approx. 10% of European passenger traffic only as yet. High-speed traffic makes up 0.07% of the total passenger traffic volume in the world.

Figure 2.4: High-speed passenger traffic [UIC, 2004]

Figure 2.5: High-speed passenger traffic in Europe [UIC, 2004]
A second effect is that mixing different train concepts leads to a rapid saturation of the network and makes, in combination with growing traffic rates, highly interwoven networks prone to disruptions.\(^\text{17}\) The Dutch network serves as an example; despite the variety in causes, most of the punctuality loss in recent years was due to so-called secondary delays, i.e. train delays on other network lines, as a consequence of a disruption on a particular line and a deliberately interwoven timetable.\(^\text{18}\) A study project is currently being undertaken in the Dutch railway sector, which proposes to 'simplify' the current network into conflict-free corridors, i.e. corridors that can be operated independently, similar to the Japanese Shinkansen network; trains will not need to cross complex station yards [Benutten en Bouwen, 2002]. The reason behind this project is the forecasted traffic growth in the Netherlands. A growth in passenger traffic by rail of more than 70% between 2002 and 2020 is hoped for, implying a growth in market share during peak hours from 25% to 35% [Benutten en Bouwen, 2003]; a tripling of transport demand is also expected for rail freight. All parties in the sector participate in the project, which aims towards a 'metro system' with frequent train departures (every 10 minutes in peak hours) and homogeneous timetables (two instead of three train types). It should thus be sufficient to expand the infrastructure selectively with extra passing tracks.

2.2.3 **Railway safety and societal risk awareness**

Finally, challenging demands for the IM stem from a changing attitude in society with respect to safety, noise and environmental pollution. Increased risk awareness leads to the proposal of stricter safety regimes. For example, the Hatfield train crash in the UK in 2000, caused by rolling contact fatigue (RCF), led to an unprecedented long reduction in train services throughout the entire network while the scale of the problem was being investigated [Railtrack, 1999 and 2000]. Another far-reaching decision concerns the integral removal of 890 kilometres of so-called 'Nefit-tracks' on the Dutch network. Problems with Nefit-track have been known for many years; the main problem is that the state of the fastening clips can in several cases not be sufficiently guaranteed. Because of the fear that traffic safety would be at stake, ProRail/RIB and the Ministry of Transport decided in 2000 that the removal should be realised within five years, causing high renewal volumes (see Chapter 6).

Another illustration of this growing risk awareness is the change in labour safety policy in the Dutch rail sector. After a number of consecutive fatal railway worker accidents, the Dutch government demanded a 60% reduction in the individual risk for track workers [ProRail/RIB, 1997a]. In order to achieve this, ProRail/RIB had to develop an entirely new maintenance regime that completely changed the existing way of planning and scheduling maintenance. The new starting point for most maintenance is that the track is not accessible

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\(^{17}\) The ideal situation is to physically separate traffic flows with different speed and acceleration characteristics, which is, usually, not allowed due to scarcity of infrastructure [ProRail/Railned, 1998b].

\(^{18}\) The punctuality level of Netherlands Railways (NS) has varied much in recent years. In 2000, it had increased to 86.5%. During that year, the NS agreed with the Ministry of Transport to achieve a further increase to 92% in 2004 [Lensing, 1999]. However, problems rapidly arose due to backlogs in train maintenance, strikes, the installation of a new traffic control system, storms and infrastructure failures. The punctuality level dropped to 80%, and the top management was forced to resign. In the first quarter of 2004, punctuality was back at 85% [www.ns.nl]. Note that NS counts a train as 'on time' if it arrives at its destination less than three minutes late; other European railways apply a five-minute limit, this means that 92% of the NS-trains were "in time".
for trains while maintenance is ongoing; this is called the ‘track gang is equal to train’ concept. This concept has been realised through a fixed maintenance roster that is included in the annually agreed slot allocation; the Netherlands is the first European country using such a regime on a conventional network [Improverail, 2003]. Maintenance tasks are clustered in packages that can be performed during the agreed monthly and quarterly slots. Railway lines and yards have been segmented into so-called work zones, which are large enough to perform the maintenance, possibly using several teams simultaneously [ProRail/RIB, 1997a]. In 2002, the Labour Inspectorate, a government agency, also interfered in the implementation of large renewal projects. The Inspectorate did not agree with the single-track renewal with renewal trains, while traffic continued on the adjacent track. The Labour Inspectorate in fact would like to see any maintenance or inspection during timetable hours to be abandoned; in future this may lead to increasing pressures for planned slots [Brasser et al., 2003]. This is why ProRail is currently exploring in a pilot the possibility to replace patrol walks (of switches) by a so-called video-inspection train.

Other important legislation in the Netherlands, subject to societal opinions, concerns the allowable working hours, safety at level crossings, and noise and vibrations caused by rail traffic [VROM, 1997]. Because standards for external safety and allowable noise levels have been tightened up, several spots on the existing rail network no longer comply with these standards; this has long been tolerated but has led to a backlog in upgrading measures in the order of € 3-5 billion [Benutten en Bouwen, 2003].

2.3 State of the art in railway engineering and maintenance

The changing environment likely creates a need for different skills and procedures in the management of rail infrastructure. This section analyses whether such changes can be recognised in the rail infrastructure sector; the results of a scan of ‘management change’ and R&D programmes is included in several of the following subsections.

2.3.1 Organisation and contracting

This subsection analyses changes in the internal management structure of ProRail, and concludes by reflecting on the extent to which this example is representative of other IMs. In the 1990s, a separate infrastructure services division was established within the NS, which was in 1997 transferred to three contractors: Strukton, Volker Stevin and BAM. After outsourcing the maintenance staff, ProRail/RIB needed contract management skills as well as technical expertise. In contrast to the UK, the maintenance contracts were not directly set up as performance-based contracts [Allen and Ogilvie, 2003; Swier and Luiten, 2003]. At first, practically all inspection and maintenance frequencies were prescribed, although they intended to develop more output-based contracts (e.g. delivered track quality). Along with the outsourcing, the decision was taken to locate the supervision of the maintenance contracts as well as the planning and tendering of renewals at regional level [Swier and Vollenhoven, 1998]. The four maintenance regions would be better able to manage these processes; this meant a drastic decentralisation of decision powers. Two important departments were therefore established in each region, being the ‘Execution Group’ and the ‘Planning Group’. In each Execution Group, multidisciplinary line supervisors became responsible for the
maintenance contracts, while project leaders became responsible for engineering and tendering the major M&R works. The Planning Groups became responsible for the regional planning process for M&R, known as the production planning cycle (PPC); a Planning Board, consisting of the managers of the regional M&R planning groups, takes responsibility for this plan.\(^\text{19}\) The Planning Board receives and authorises the Production Plan recommended by the Regions, although it must be noted that the ProRail/RIB Management Team is the ultimate decision maker.\(^\text{20}\)

The PPC has gained an important role in the organisation, because of the importance of timely planning of budgets, possessions and M&R work to be (publicly) tendered. The PPC is illustrated in Figure 2.6; the rectangular boxes describe activities to be performed, while the boxes with a curved side are input or output (data). The grey part concerns preparations that need to be made in advance of the PPC. Once the regions have their first list of proposals for major M&R available, the plans are reviewed at regional level. The resulting regional Production Plan, generally with a five-year outlook, is sent to central headquarters. If necessary, proposals are reviewed in interregional meetings of planners and technical experts. When the plan for the year \(n+2\) is accepted, it becomes part of a formal management contract between each region and the central management.

![Figure 2.6: Production Planning Cycle for maintenance and renewal (simplified)](image)

The Production Plan is in fact the central ‘piece of paper’ in the planning and implementation of periodic M&R (see Box 2.1 on the next page for a discussion); the PPC should therefore realise the following objectives [Van Zelm, 1998]:

\(^{19}\) The two key staff units found in each region are the Execution and Planning Groups. The Execution Groups are responsible for implementing the programme of periodic M&R and for supervising the contracts for minor maintenance. The relatively small Planning Groups were established in 1998 for planning periodic M&R works; this should allow a longer-term view. As of mid-2004, a new re-organisation is expected for the regional Execution Groups.

\(^{20}\) The ProRail/RIB Management Team for Preservation/Maintenance consists of the Director of Preservation and the four Regional Directors.
- uniformity and transparency of proposed M&R works among the regions;
- timely data collection on performed works and infrastructure quality;
- timely information for negotiations on track possessions and funding;
- timely acceptance of plans in order to organise competitive, efficient tenders.

**Box 2.1: Proposition and use of the M&R Production Plan**

<table>
<thead>
<tr>
<th>The Production Plan is the central decision in the planning of all periodic M&amp;R over the next few years. In ProRail’s production plan, the following factors are to be considered [Van Zelm, 1998]:</th>
</tr>
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<tbody>
<tr>
<td>- inspections available on the state/ degradation of the infrastructure;</td>
</tr>
<tr>
<td>- infrastructure quality standards for safe and reliable railway operations;</td>
</tr>
<tr>
<td>- budgets made available by the infrastructure owner, which might require a prioritisation;</td>
</tr>
<tr>
<td>- track possessions made available, which might require a prioritisation;</td>
</tr>
<tr>
<td>- other constraints such as available resources (contractors, labour, machines) and materials; and,</td>
</tr>
<tr>
<td>- other objectives such as minimised noise pollution and costs, and maximised productivity.</td>
</tr>
</tbody>
</table>

In order to create a systematic approach, a strategic maintenance concept should define how the above input is used in M&R planning. The Production Plan directly determines:

- **expected** infrastructure quality and reliability and, hence, costs of unplanned maintenance;
- the **planned** costs and use of resources for periodic maintenance and renewal; and,
- **required** spot maintenance in order to retain the infrastructure at the required quality standards.

The Production Plan indirectly determines the **life-cycle costs**, together with:

- the realisation of the Production Plan;
- the effectiveness of performed minor and periodic M&R;
- the loads actually generated on the infrastructure; and,
- the actual financial, physical and operational conditions.

Since 2001, it is obligatory for regional staff to deliver a life-cycle cost analysis, or refer to the outcome of an earlier analysis, for each project proposal that exceeds € 0.5 million. This requirement is a direct result of the so-called ‘life-cycle management (LCM) project’ that ProRail/RIB commenced in 1998. LCM was explicitly initiated to improve the quality and transparency of design and maintenance decisions [ProRail/RIB, 1998a]. At first the project aimed to systemise the entire process of engineering and maintenance by using life-cycle cost analysis in every step of the design and maintenance planning (see Figures 2.7 and 2.8). However, in 1999, the development of an encompassing “LCM process” was deemed a step too far. It was decided to develop a simple LCC Calculation Tool, where staff members stipulate their own expectations in terms of residual lifespans, unit costs for construction and M&R, and possession time needed for construction and M&R. The programme calculates total life-cycle costs for the suggested solutions under these assumptions; a limited sensitivity analysis can also be included. A **preferred alternative** is selected based on this outcome and possibly other qualitative motives. The tool could be developed and implemented quickly; all M&R planners were invited for training in 2000 [ProRail/RIB, 2000b]. Using the tool, assumptions for projects become explicitly available in terms of expected lifespans and maintenance levels; the performed LCM analyses are made available to all ProRail staff through the corporate computer network. A database, the so-called Rail CaseBase, is currently being filled with data on unit costs of construction and M&R, which staff can then use in the LCC analyses.
Figure 2.7: Proposed LCM process scheme for the Construction Department [ProRail/RIB, 1998a]

Figure 2.8: Proposed LCM process scheme for the Maintenance Department [ProRail/RIB, 1998a]
In 1999, the first step was taken towards organising the maintenance process on a more output basis by gradually introducing output-based process contracts (OPCs) for maintenance and failure repair, also called ‘process maintenance’ in the Netherlands; the OPC contractors are generally awarded the contract for five-year periods [ProRail/RIB, 1999b; Snippert, 1999]. The objective of OPC was, and is, to develop a ‘healthy’ customer/supplier relationship, in which the contractors do not perform prescribed tasks, but provide a full maintenance service; the intention is to control them on the basis of the quality and performance supplied. This should stimulate innovative thinking, customer orientation and efficiency, and only applies to performance aspects that can be well measured and controlled [Swier and Luiten, 2003]. Figure 2.9 shows that the OPC contracts focus on a different type of service specification than the PPPs mentioned in Section 2.2.1; moreover, much inspection and maintenance work are still calendar-based.

The functioning of the existing OPC contracts is currently evaluated in a project of ProRail and the contractors, named OPC Plus; this will result in revisions to the specifications, procedures for exchanging data and for communication in the event of failures. Work specifications give currently still few incentives for the contractors to improve their work process. OPC Plus will hopefully be a step forward in that respect. At the same time, data systems from ProRail and its contractors will be coupled in order to create a shared database, which should allow each of the parties to improve the quality of its particular share in the maintenance process (see Figure 2.10 on the next page).

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21 This trend can also be seen in the procurement of materials, although this is still in an early phase. An example is a contract between ProRail and a switch supplier, regarding minimum times between failures.
A development that complements those already mentioned concerns the increasing efforts to benchmark infrastructure costs and performance levels with other railways, in order to learn from best practices (see the UIC InfraCost study). A key challenge is to make cost/performance levels of different infrastructure systems comparable. The UIC InfraCost study [2003] and Swier [2004] provide examples, which are included in Figures 2.11, 2.12 and 2.13. The figures are an attempt to explain life-cycle cost differences. These differences prove to be partly explainable by traffic conditions, such as intensities (train kilometres per track km), axle-loads and speeds. "LCC" in the figures stands for the direct costs of maintenance and renewal only.

Figure 2.10: Concept of a shared asset database [supplied by Strukton Railinfra]

Figure 2.11: Costs of ownership versus traffic intensity [Swier, 2004]
Figure 2.12: Costs of ownership versus tonnage on the track [Swier, 2004]

Figure 2.13: An explanation for the cost difference between Dutch and U.S. Class I rail network [Swier, 2004]
It is hard to judge to what extent the organisational changes seen in the Netherlands have also occurred in other countries, because an 'insider's analysis' is required. Organisational structure, culture and procedures also depend partly on underlying national customs and political views. They can also fluctuate over time, as shown by Network Rail's decision to retake direct control of the maintenance process. Nevertheless, Saccardi [2003] provides an indication that similar processes seen at ProRail are also at stake, e.g. in Italy at Rete Ferroviaria Italiana:

'The current situation is characterised by a hardly standard manner to express the exigencies of maintenance. RFI is divided in 15 Compartamental Directions, each one responsible for a part of the national infrastructure. (...) The Maintenance Central Direction, located in Rome, has no instruments and methods to discuss the requests coming from the territory'.

The European Standard 50126 [CENELEC, 1999] is a strong indication that the described work of ProRail to create more transparent, output-driven processes is a common struggle of many European railways today. The standard, which is included in Section 3.4.1, prescribes a formalised process to design and demonstrate RAMS levels of railway systems. IMs can use it for structuring their own management procedures as well as for the procurement of new equipment, entire railway systems, and maintenance services.

2.3.2 Innovations in the rail infrastructure system

In addition to redesigning management concepts, technological R&D is another important indicator of the progress made in controlling and improving the cost and performance levels of the rail infrastructure. The following subsections focus on technology development, system design, maintenance methods, inspection technology and information systems development. N.B.: although these areas are discussed individually, the developments are closely related.

Many suppliers, ranging from single-component suppliers to those supplying entire track or signalling systems, are contributing to R&D in the field of infrastructure technology. R&D efforts focus on delivering components or systems that have improved reliability, safety, maintainability and functionality properties (e.g. allowable speeds, loads and traffic densities).

The process can be illustrated by the improvement in the construction of the rails. After the Second World War, many countries used designs of their own (e.g. NP46 in the Netherlands), but international standards were adopted later that often implied a heavier rail: UIC54 rails and in many countries today, UIC60 rails. Instead of jointed rails, continuous welded rails (CWR) became the new standard, which resulted in greater passenger comfort and less maintenance. Head-hardened rails and manganese switch frogs were then introduced to reduce wear on the curves and lines with heavy loading. Improvements to the rails were complemented with innovations in the design of sleepers, fastening systems and ballast bed (e.g. concrete sleepers, geotextiles, and chemical binders to bond ballast together).

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22 Principal cause is Railtrack/Network Rail having lost understanding of the key influences on M&R expenditures [Allen, 2003; Modern Railways, April, 2003].
In addition to these gradual improvements, completely modified track types have also been developed. Firstly, new ballasted track systems have recently become available; these have a different sleeper design than conventional ballasted track systems. Germany developed a wide-sleeper track ('Breitschwellen'), which results in 'a continuous slab of discrete elements'; the weight of the sleepers themselves doubled, but the pressure on the ballast bed almost halved as a result of the new shape, resulting in considerably less (geometric) maintenance [Cronau, 1998]. Austria developed a frame sleeper track ('Rahmenschwellen'), which adds 'a longitudinal beam' to the traditional sleeper concept. Subsidence has been reduced by two-thirds, thanks to the more continuous support of the rails and the horizontal rigidity of the 'sleeper grid' [Riessberger, 2002]. Finally, Japan studied so-called ladder sleeper tracks [Read and Wakui, 1999].

Considerable technological progress has been made in the development of ballastless track systems that replace ballast by concrete or asphalt beds. A distinction can be made in slab tracks providing discrete support of the rails, similar to ballasted track and those providing continuous support. The discrete support systems can be further distinguished in those using either concrete sleepers or blocks that are embedded in concrete and those where the rails are directly fastened onto prefabricated slabs (e.g. Shinkansen or Bögl track) or the civil substructure [Quante and Ogilvie, 2001]. In some countries, slab track has become the standard choice for certain situations (e.g. new high-speed routes in Japan and Germany, level crossings in the Netherlands, and subway tracks and switches in Madrid) [Ando and Aoki, 1999; Bauman, 2003; Melis, 2004]. It is usually more expensive to construct, but construction costs have dropped thanks to the introduction of reliable in-situ production methods (e.g. pavers). The embedded rails system (ERS) is without doubt the most revolutionary concept, because continuous support is provided through an elastic compound, usually consisting of cork and polyurethane. ERS can be constructed with slipform pavers and allows new, optimised rail types (e.g. SA42). In 2002, a new type of ERS was installed on a high-speed test section in Spain; prefab elastomeric pads were used in order to improve constructability and maintainability [Balfour Beatty, 2002].

However, IMs do not have an easy task when considering new technology. Consideration has to be given to the additional costs involved and the fact that new failure modes can occur due to changed properties of the track or its maintenance regime. It is, for example, well known that concrete sleepers are more susceptible to corrugation of the rails and that rigid track systems are more prone to components cracking [Esvid, 2001; Oostermeijer, 2003]. As an illustration, Smulders et al. [2003] confirm that it is difficult to identify the causes of current problems with rolling contact fatigue, because changes in track design over the past decade coincided with changes in vehicle design and maintenance. Problems often lie in dynamic track properties [De Man, 2002]. Scientific research should be able to help, but De Man [2001] notices:

'Examples of finite element simulation data in railway track systems are still very rare. This is a remarkable difference with many other structures applied in civil engineering, for which calculation standards have been drawn up (...). In railway engineering, laboratory research and simulation software should be developed further to establish their position'.
The major advantage of slab tracks, compared to the track construction in ballast, is the high structural quality and fixed geometry, which leads to very low M&R needs, around 20-30% those of ballasted tracks [Zoeteman, 1999a; Ando and Aoki, 1999; Esveld, 2001]. However, these slab tracks become prone to the risk of cracking in the event of inapt construction or soft subsoil conditions, though this risk can probably be dealt with (e.g. the development of DeckTrack for soft soils) [Esveld, 2003; Ando et al., 1999]. Moreover, methods for an affordable construction process, (in short time slots) on the existing network are not yet available.

Nevertheless, there is no doubt that IMs are profiting from the described technological progress. Roney [2001] provides evidence from North America. He refers to research by Massachusetts Institute of Technology (MIT), which show that these innovations have reduced track costs in U.S. mainlines by $1.5 billion between 1970 and 1998:23

’Many of us are profiting from lighter cars, improved suspensions, rail and wheel re-profiling, heavier axle loads, track maintenance planning systems, high throughput locomotives and longer trains. Our track/train dynamics environment is more controlled. We are wearing components less and consuming less energy in the process [thanks to the innovations in track and freight-car technology]. Our operating costs have declined steadily over this timeframe, and surprisingly in step with one another’.

Technological progress is also made in the fields of power supply and signalling, leading to a broad introduction of electronics and information technology and, in some countries, more powerful traction systems.24 Important new developments in Europe include the introduction of GSM communications for Railways (GSM-R) and the current tests of ETCS/ERTMS [Bergmann et al., 2001].25 GSM-R provides the railways with a dedicated GSM band for mobile data communication, while ETCS/ERTMS is a system that will need less, failure-prone, wayside signalling equipment. In the future, ETCS (European train control system) level 3 should allow GSM-based moving-block train control, in which headways of individual trains are calculated on the basis of their actual characteristics. They can replace the fixed signalling blocks, which are too long, as they are always based on worst-case conditions (i.e. the braking of a heavily loaded freight train). It allows more traffic on the same line as well as European standardisation. Similar efforts are being seen in Japan and North America [Fukuda and Manabe, 2003; Polivka, 2003]. Where ETCS is meant for main lines, other systems have emerged for regional lines; the main objective on these lines is to create leaner infrastructure, thereby reducing operating costs. An example is the German FunkFahrBetrieb system; train drivers can create their own safe driving space without

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23 Similar insight on the infrastructure cost reductions achieved by new technology has not been found for Europe and Asia. With regard to the East Asian railways investigated in the UIC InfraCost study, it was found that their infrastructure expenditures per track kilometre are a factor 3 higher than in Europe, because of their focus on quality and reliability. This high level of costs is commercially not a significant burden for them: M&R expenditures per passenger and net ton kilometre are only about 50% of the European level.

24 Over the next few years the Netherlands will see the application of 25 kV AC power on the Betuweline, a new freight route, and the new HSL South. The existing network uses 1500V DC, and studies have been going on for some time regarding whether (and how) to upgrade this [Hengeveld, 2000].

25 ETCS/ERTMS stands for: European Train Control System and European Rail Traffic Management System. It is not so much a system in itself, but rather a set of detailed specifications for the future suppliers of CCC systems which are interoperable throughout Europe.
interference from a traffic control centre, for instance for putting switches into the correct position [Haverman et al., 1999; Hofestadt et al., 1999].

It can be concluded that suppliers are actively developing new products that should improve functionality and RAMS and, to some extent, cost levels and standardisation. This poses investment decisions for IMs, in which costs, risks and (transport and infrastructure) performance have to be traded off against each other.

2.3.3 Maintenance technology and work methods

Although mechanisation started late, many improvements have been made in railway maintenance over the last 30 years. As an example of this progress Esveld [2001, p. 360] describes the relationship between working speed and intervals of required intervention over the years of tamping machines. It shows that speeds increased and intervals extended as a result of the improved quality of tamping machines. Where the output of the first machines, in the 1950s, was 120 metres per hour, the latest machines realise more than 2 kilometres per hour. Other advantages include a shortening of the times for approaching the work site, setting up and finishing the work.

Several factors have driven this process. An obvious driver is the availability of new information and communication technology (ICT), which enables suppliers to develop more advanced machinery. A second facilitating factor concerns stricter regulation and protocols with respect to quality, safety and liability in construction and M&R processes (see Section 2.2.3). This includes the introduction of required quality systems based on ISO9001/4 standards [ISO, 2004]. All in all, they trigger contractors to introduce more industrialised work processes [Van den Hurk, 2003].

Nowadays, high-output machines are available for any type of major M&R work related to tracks, switches, and catenary; examples are machines, or entire train units, for rail grinding and re-profiling, straightening welds, catenary renewal, track relaying, stoneblowing, ballast cleaning and dynamic stabilisation, and formation rehabilitation. Like tamping machines, they have improved productivity levels over time, yet the larger M&R works (such as renewal) still have important scale effects, i.e. longer slots result in higher productivity levels. The development of mechanised stoneblowing is worth mentioning as a recent innovation, from the UK, which can be particularly useful for older, worn-out tracks (those which need tamping every six months or less). The basic principle is to blow a measured quantity of small, but strong stones under the sleepers. This improves track settlement significantly on those lines where tamping has become ineffective due to the so-called memory of ballast; ballast beds in bad tracks quickly deteriorate to the shape they had prior to the tamping operation [Lichtberger, 2000; Esveld, 2001]. Another innovation concerns the machinery for spot maintenance. Tamping machines usually restore the track to the originally designed alignment, as stored in the computer, without considering the subsequent relocation of the track while deteriorating; this can lead to a quick return to the former state. Lichtberger [2003] mentions that spot-tamping machines, which do not follow that approach, can reduce maintenance costs by 75% and maintenance time by a factor of 5, when applied to irregularities in the track that occur for the first time. A final innovation worth mentioning is 'design overlift tamping', which seems not really to be tested or applied yet, but which can be
performed when the real track geometry is known. An overlift is consciously made in the track at those spots showing relatively strong settlement in order to allow for expected deformations, which should allow the quick recurrence of these spots.

ICT also gains a place in the work processes for minor maintenance. Systems have been introduced recently to automate the scheduling of maintenance jobs [Talsma, 2004; MRO, 2004; Dowell and Baker, 2004]. Such programmes allow required maintenance jobs to be clustered into task plans, based on the estimated time needed and available slots/shifts for M&R; work orders are automatically forwarded to technicians who need to perform these tasks. After these have been completed, they can update the system via palmtops (or handheld computer) and include eventual defects found.

Last but not least, the introduction of ICT also takes place in the inspection of infrastructure quality and condition. This is probably an area where developments have been most ‘turbulent’. Train-bound measurements and patrol inspection, or scouting, have always been used to guarantee railway safety, but ICT has provided new possibilities for an affordable data collection and storage process. Firstly, computer-based technology increasingly supports the patrol inspections through hand-held equipment, such as laptops or palmtops. Secondly, track-recording cars (TRCs) that measure track and pantograph properties are being equipped with ‘digital scouting’ tools. Pattern/signal recognition is the essential new technique. For example, rail profiles can be measured with cameras and light-slicing methods; the contours of the railhead are recorded and, via analogue-digital conversion, the rail profile can be linked to the geographic location. This is then compared to the correct ‘target profile’, which is stored in the computer, and deviations are automatically signalled [Zijlstra, 1999]. Rail defects, such as corrugation, worn-out welds, imprints, missing fasteners and RCF, can now be identified. In order to support the off-board analysis of measured data, visualisation software has been developed to combine all kinds of measurements on a single computer screen. Different colour schemes are used for exceptions, i.e. measurements surpassing pre-set values, and raw data are transferred where possible into quality indices. Examples are IRISsys and ORIM; these systems (have the potential to) combine work history and track quality data on one screen. This allows an analysis of work effectiveness and root causes of problems [Esvel, 2001, pp 515; Oehler and Erdmann, 1996; Optram, 2003]. Thirdly, remote condition monitoring (CM) applications are becoming available for crucial equipment, thus avoiding failures and traffic disruption. CM is based on sensors that measure quantities relating to the state of the component. GSM-R, fibreglass cables, and Internet technology can be used to transport and present the data to the maintenance staff. This raw data is analysed to extract hidden condition information [Van der Wal, 2000]. An example is the power consumption needed by a switch motor. Rising power consumption under equal conditions (e.g. outside temperatures) indicates incorrect geometry, malfunctioning parts, or motor problems. Examples of equipment in which CM can be used are interlockings, switches and level crossings. Examples of applications are the Roadmaster-2000, POSS and CEDIAC [Fraunhofer Institute, 1999; Esvel, 2001, p. 494; Redecker and Brugman, 2003]. The POSS system is now installed on the most crucial switches in the Dutch network. The EU-funded project Remain provided estimates of possible life-cycle cost reductions [Fraunhofer, 1999].
Remarkably, inspection (traditionally an internal IM work process) is becoming an international market. This is reflected in the emergence of dedicated inspection companies, such as Eurailscout and Mermec, and the development of international standards for (geometric) infrastructure quality [see CEN, 2000]. Better inspection can have a positive effect on the performance of IMs over the next few years. Riessberger [2000] argues that frequent inspections have reduced traffic disruption and maintenance costs on critical sections of the French TGV (high-speed train) lines.

The indicated developments are not only seen in track and catenary inspection, but also in condition measurements of wheels, tunnels, bridges and substructure. An innovation worth mentioning is ground penetrating radar (GPR), which enables a detailed study of the condition of ballast bed and earthworks. Reflections of electromagnetic pulses by the GPR reveal the material properties and thus foul ballast bed conditions, drainage problems, and hidden settlements. Another related development is research into a high-speed deflectograph, which can measure the vertical stiffness of railway tracks [Rasmussen and De Man, 2000].

2.3.4 Computerised maintenance planning systems
Over the past two decades serious efforts have been made to develop so-called computerised maintenance management systems (CMMSs). These systems use measured, empirical data to plan M&R works in a systematic and objective way, thus contributing to a better maintenance process through [Esveld and Roney, 1993]:

- optimum allocation of resources across the network;
- improved understanding of reasons for performing or deferring work;
- the ability to predict future resource requirements (long-range budgeting);
- a reduced risk of neglecting to maintain a critical location; and
- a systematic approach to proposing production plans and bills of materials.

The main hurdle in developing these systems lies in the presence of many influential factors that culminate in the degradation of the assets. The systems should be able to predict degradation patterns and estimate the effectiveness of interventions. Figure 2.14 visualises the problem and shows a theoretical degradation pattern for the geometry of a railway track; the quality of track installation is reflected in the initial quality level. Track roughness increases with the amount of tonnage carried (million gross tons, or MGT). At some point, intervention is needed. The IM therefore needs to define intervention levels or thresholds. Several options for intervention are shown. Firstly, the broken lines show that replacing the track can be postponed through timely rehabilitation (tamping). After some time the effectiveness of this maintenance may become inadequate, which is reflected in a decreased interval. Replacement becomes necessary before the track condition passes the ‘operational limit’ when safety of the traffic may be at stake. The figure also shows an entirely different option (at 120 MGT), which is to upgrade the track system, e.g. with an improved ballast bed; the reduced amount of maintenance and extended life should be traded off against this investment.
Figure 2.14: Degradation of track geometry [Ebersohn and Ruppert, 1998]

Almost all these CMMSs focus on assisting track M&R, because this is the most cost-intensive area and track condition degradation can be predicted fairly well. Esveld and Roney [1993] describe the early examples. The systems are meant to assign priorities to M&R work, through projecting the years in which track quality in a given track segment will first fail to comply with target standards (or thresholds). In order to do so, asset (location and history) data, measured quality data, and planning rules and thresholds are combined. Some systems allow additional constraints and objectives to be added, e.g. budget limits and scale effects in M&R works; the systems can then use this input to generate an optimal work planning. Over the past decades (prototypes of) more advanced systems have become available. These are discussed below in order to give an overview of the current state of the art.

In 1991, the UIC started an important research project that, in 1997, supplied a rule-based expert system, named ECOTRACK, to enable IMs to plan M&R on the basis of well-defined technical and financial rules [Zaalberg, 1998; Rivier, 1998; ERRI/UIC, 1999]. The project was financially supported by 24 railway operators and was implemented by a group of experts from around 15 railways. It resulted in a phased process for generating an M&R work plan, as depicted in Figure 2.15.

Input for the planning process include track measurements, M&R work histories and a rule base. The first three steps are based on an analysis of the track condition with a gradually increasing level of detail. The initial diagnosis calculates the rough M&R needs, while the system points the user at desirable, additional data for more detailed diagnosis (e.g. data on the percentage of fine materials in the ballast bed). The work plan for each track component is refined in the detailed diagnosis. Linear degradation forecasts are then developed, and the preliminary work programme is improved in terms of clustering renewal works, which are ‘close’ in time and space. Finally, the fifth level provides a number of statistics, such as the overall network costs expected for the coming 10 years. Although the rule base contains
default rules, feasibility studies held during the last few years made clear that modifications in the database and rule base need intensive support from ECOTRACK specialists.

Figure 2.15: ECOTRACK - the calculation process for composing M&R plans [ERRI, 1999]

Railways and IMs involved in these feasibility studies were convinced of the strategic value of such a system, but none have yet made the final decision to use it in practical track M&R planning [Jovanovic, 2003]. ECOTRACK has been used for a couple of years at the central headquarters of the Belgian railways for reviewing M&R plans. In the UK, a modified version of ECOTRACK was used to develop an auditable track renewal volume forecast during a strategic study [Roberts, 2003]. However, practical problems came to light in most countries (unavailability of basic inventory data, installation dates, annual tonnage data, work histories etc.). Also, ECOTRACK does not yet take constraints concerning the availability of maintenance slots into consideration. An obstacle proved to be a rigid code-structure (e.g. inflexible deterioration models and infrastructure segmentation). Support for further development lacked in the period after 1998. In 2004, ECOTRACK was transferred to the engineering company named Arcadis, which is currently undertaking a revision and redevelopment.

An example of a fully operational system for planning track maintenance that uses detailed track deterioration data, is found in the Central Japan Railway. JR Central uses two connected systems, RINDA and TOSMA, to plan track tamping on the Tokaido Shinkansen line between Tokyo and Osaka. RINDA is a ‘descendant’ of SMIS, the management information system of the former Japanese National Railway. RINDA is specifically used for track management and contains all relevant data, such as track line form and structure, cumulative tonnage, track state, rail temperatures, ballast deterioration, patrolling reports, and performed maintenance works [Ohtake et al., 1998]. The digitally stored inspection data from
the track-recording car is entered directly into RINDA after every new campaign, and every night the latest data is distributed to the computers at the 20 maintenance depots along the line. Depot staff can only access the data for their line section. Two or three persons per depot are able to work with TOSMA and RINDA and they can produce the information needed for the maintenance scheduling staff [Zoeteman, 1999b]. Computers at the contractor’s offices are also linked to RINDA; contractors are allowed to put some items into RINDA themselves.

TOSMA is a sophisticated application that utilises the data from RINDA to make detailed forecasts on the degradation of 20-metre track segments [Ohtake et al., 1998]. TOSMA predicts irregularity growth for periods of 10 days, one month and three months, based on the maximum irregularity value measured within the segment. The objective is to avoid rapid track irregularity growth, which is why spot tamping is used in addition to overall tamping; the amount of necessary spot tamping can be estimated reasonably accurately using the data available in TOSMA [Sato, 1998]. The quantity of work over a period of one year can be forecasted fairly well, which is why maintenance contracts can now be made one year in advance [Zoeteman, 1999b]. In addition, TOSMA calculates a so-called ‘rectification ratio’, which measures the effectiveness of the tamping work performed by contractors.

TRIS, developed by a Dutch contractor, is a system worth mentioning because of its flexibility to include different degradation modes in its models [Van den Beemt, 2001]. TRIS’s aim is to develop condition-based maintenance strategies for tracks, switches, and the civil structures. Where ECOTRACK focuses more on a few quality degradation patterns needed for planning heavy M&R work, TRIS can handle a variety of maintenance tasks. It needs expert judgements and data from both patrol inspections and track-recording cars; checklists have been developed that can be used during global and detailed surveys by the patrol teams. Users can add their own linear or non-linear models to describe the behaviour of a specific degradation mode under the effect of loading. The user defines in advance the possible types of M&R and the intervention levels to keep track components within desired condition limits. TRIS can deal with qualitative judgements, such as ‘beginning’, ‘intermediate’ and ‘advanced deterioration’. Calculated strategies are ranked on the basis of the current net value for the first 20 years. Figure 2.16 shows the phased calculation process. A disadvantage of TRIS may be that considerable data is needed for an accurate prediction.

![Figure 2.16: TRIS repetitive process for composing M&R strategies (Van den Beemt, 2001)]
Finally, several railways in North America and Asia have developed planning tools that use detailed empirical data to plan preventive maintenance, such as grinding and lubrication. Keefe [2001a] describes how the MTR Corporation in Hong Kong uses their Rail Management Model:

'\textit{The rail deterioration rate with and without grinding is derived from the technical parameters of the model. The financial/cost factors of wheel and rail maintenance are as important as the technical parameters in minimising the life-cycle costs. The model provides the optimum grinding cycle (in months) for each curve on the network, as well as the optimum lubrication regime}'.

Despite the aforementioned initiatives and (to some degree) operational systems, considerable R&D is still needed with respect to having meaningful CMMSs, as addressed by Problem Statements 2 and 7 from Committee A2M06 of the Transport Research Board [TRB, 2004]. Statement no. 2 stresses that effective, predictive models that are sensitive to such variables as operating speed, annual tonnage, and axle-loads hardly exist. Some models have been developed, but: 'they were all directed towards heavy freight traffic, and low volume lines have been virtually ignored'. It states that having effective planning models is a necessity, considering shrinking engineering workforces and limited M&R budgets. Statement no. 7 adds that, apart from predictive degradation models, significant effort is still needed to develop the general structure of computerised management systems, in terms of key asset data, (quantitative) business objectives and engineering rules. Section 2.3.5 discusses this problem further.

\subsection*{2.3.5 Computerised asset registers}

Considerable parts of the R&D budgets of many IMs have been used to develop database systems that are capable of storing and linking measurements, work history and cost data to specific assets and segments and components of assets. Without such systems it is difficult to employ available inspection data and planning systems.

A number of issues have to be dealt with in developing usable, computerised asset registers. Firstly, data has previously been used more for accountancy purposes (e.g. labour hour reports) rather than for tracking maintenance performance of individual assets; as a result, a lot of data, if already available in digital format, is stored in a variety of databases that are difficult to link to these assets. Nystrom [2003] describes this situation well. He mentions that there are around 200 data collection systems directly or indirectly related to railway systems in Sweden, of which 40 are directly related to infrastructure performance and train operations. He provides an example:

'\textit{The infrastructure condition is described in several systems, e.g. Bessa containing inspection reports, Ofelia containing failure reports and Strix containing track irregularity data. For example, if in the course of inspection an inspector comes across a loose bolt, the notification is entered into Bessa. However, if the incident is discovered by another employee, the fault is entered into Ofelia}'.

Secondly, apart from the myriad of stand-alone databases and paper-based archives found at many European IMs, an additional problem is that basic asset (location) data is often already hard to use and unreliable. A reason for this is that in the past many reconstructions of the rail infrastructure were not well recorded or properly included in the historical asset registers [Esveld, 2001, p. 605]. Another reason is that different track annotations, i.e. location indicators, are used. For example, Jovanovic and Zoeteman [2002] describe how different annotations (geocodes, kilometre posts and work zones) are all in use in different information systems needed for track M&R planning at ProRail. Thirdly, irrespective of the chosen annotation, segmentation of the rail infrastructure remains an important design issue in the development of asset registers. Railway tracks and overhead lines are linear assets; this leads to specific maintenance features and problems, compared to machines in a factory. Conventional rail networks are ‘patchworks’ of track systems with different installation dates and component qualities; usually, many different track systems can be found on relatively short line sections. Each can show widely differing behaviour in terms of degradation, because of different conditions (e.g. subsoil quality) and maintenance treatments over the years [Sato, 1998; Esveld, 2001]. For this reason, it should be possible to define the segments in the asset register in a flexible manner, in order to fit them to physical differences found in the track.

Many railways and IMs now have computerised asset databases that can be accessed company-wide, which are more or less successfully used in the planning of M&R and which are, to some degree, integrated into planning applications. Examples of asset database systems include [ImproveRail, 2003]:

- the Italian RETE2000 system;
- the Swiss DFA system, which is based on a Geographical Information System and contains data on past, present and future (expected) infrastructure condition;
- the DB Netz distributed system, consisting of IIS, PRINZIP and other databases, which are all linked through the GRAND interface system;
- MIMS, which is used in the UK, Hong Kong and Australia [Keefe, 2001b];
- SAP R3, which is used in many railways (e.g. Portugal, the Netherlands and Italy).

The problem of segmentation proves to be significant in general purpose enterprise resource planning (ERP) systems, such as SAP R3, when they are deployed for railway infrastructure; despite significant investment these systems are not yet used for maintenance planning, but for relatively simpler tasks such as incident recording, spare part management, and financial accounting [ImproveRail, 2003]. Plans for further R&D seem to have slowed down in the aforementioned railways.

Remarkable progress has occurred over the past decade in the field of asset locating techniques, and this progress allows railways that lack reliable databases of track layouts to overcome this problem. These techniques allow such databases to be developed relatively quickly. The simplest technique uses orthophoto technology to convert aerial photos into digital images and add geographic coordinates. The images are overlaid with so-called ‘vector elements’ that represent the railway assets [Esveld, 2001]. Other techniques are based on video surveying, laser scanning and global positioning system (GPS) satellites; examples are the train-bound OmniSurveyor and the helicopter-bound Fli-Map. Ebersohn et al. [2001]
describes in detail how Amtrak (the US passenger railway) and Spoornet (from South Africa) used the helicopter-bound system for setting up an asset database. Several other railways have used this technique recently [Jovanovic, 2003].

2.3.6 LCC systems and studies

A final R&D field over the last few years concerns the development of decision support systems (DSSs) for analysing life-cycle costs of railway designs and maintenance strategies; several examples of their use in strategic studies of IMs are now known. These are mostly used to review design alternatives and maintenance policies. Time horizons of 25 years or more are used to evaluate cost-effectiveness of solutions on a system-wide basis, thereby often including costs of traffic disruptions.

Since such types of strategic choices have a more unstructured character and partly require expert judgements and aggregated performance data (e.g. obtained from benchmarks of similar maintenance strategies or systems elsewhere), flexible computer models are needed with capabilities for 'what-if' and sensitivity analysis. Although the DSSs should be able to function as part of the CMMSs from Section 2.3.4, they all seem to be stand-alone systems. A number of known applications are discussed below. Although the examples provide an extensive overview of the state of the art in this field, they may not be comprehensive. Railways and IMs often consider such studies to be proprietary and confidential.

A first example is TRACS, which was developed by AAR (Association of American Railways) and MIT (Massachusetts Institute of Technology) [IHHA, 2001]. TRACS combines engineering-based deterioration models for track components and switches with life-cycle costing techniques to estimate track maintenance and renewal costs as a function of route geometry, track components, track condition and traffic mix. By running TRACS repeatedly while systematically varying the input parameters, the analyst can estimate the economic effects of changes in maintenance or traffic policies. A user group provided technical data for the calibration process and for further development of the system. Several Class I railways used TRACS, usually assisted by AAR staff, for at least the following purposes [AAR, 1997]:

- technology assessment: analysing the effects of heavy axle-loads on track costs (MIT, AAR, and R&D and the strategic planning groups of two Class I railroads);
- situation-specific costing: analysing the incremental track costs of an additional unit coal train on an entire route;
- budgeting: analysing the number of rails to be renewed over the next 10 years, and the expected maintenance budget over the next five years;
- rationalisation analysis: analysing the impacts of rerouting traffic on the maintenance costs; and,
- costing of transportation services: support of contract negotiations for providing rail movements for intermodal services, along with a model for energy consumption.

TRACS takes into consideration the fact that data is often unavailable, impractical to collect or hypothetical (what-if scenarios). The recommended approach is to first obtain an order-of-magnitude answer before deciding to pursue a detailed analysis. In this case it is
reasonable that the TRACS operator establishes a set of assumptions and that the decision maker determines whether or not the outcomes obtained are sufficiently detailed. TRACS is equipped with AAR-approved default values and requires additional data on track curvatures, rail materials, current component ages or conditions, typical component lives, installation and replacement costs, and maintenance and repair practices and costs.

Another North American example is TrackShare by Zeta-tech, which can be used for allocating the costs of shared traffic in so-called open access regimes. It contains models for determining incremental track maintenance costs that can deal with different types of traffic (heavy haul, moderate axle-load, intermodal trains, and high-speed passenger trains) [ZetaTech, 1998]. It uses so-called 'engineering adjustment factors' to quantify the relationship between traffic volume and track maintenance costs. Relative damage caused by extra trains is estimated on the basis of vehicle and track characteristics (e.g. axle load, speed, bogie type, grade, curvature and rail type). Finally, the average maintenance expenditures are adjusted for the relative damage.

An example from Japan comes from Miwa et al. [1999], who perform regression analyses on detailed datasets of track (geometry) measurements, collected through systems such as TOSMA, in order to improve maintenance strategies. Although these are not used for life-cycle cost estimates, this would appear to be a feasible next step.

A well-known LCC example from Europe comes from Veit [1999]. His model calculates internal rates of return for different maintenance strategies. Applications include an analysis of track maintenance cost impacts from different locomotives and a revision of existing track M&R practices in the Austrian Federal Railways (OBB). During this last project, the entire network was categorised into standard track categories, using criteria such as traffic density, curve radius, and subsoil conditions [Veit, 2000]. Typical 'life cycle activity profiles' were developed for each of these categories, using expectations from knowledgeable track maintenance planners and data on historical M&R volumes. These profiles describe the necessary M&R during an average track lifespan (see Figure 2.17 for an example). Using these activity profiles, it is possible to compare the life-cycle costs of different maintenance practices, operating and subsoil conditions, including costs of line closures and temporary speed restrictions.

![Image](image_url)

**Figure 2.17: Life cycle activity profile for a standard kilometre Westbahn [Veit, 2000]**

The French Railways Authority (RFF) developed a tool named MOVE, which generates a theoretical M&R work plan for the tracks on the entire French network for a period of 50 years with a minimal amount of input [Levi, 2001]. Life expectancies are
calculated as functions of the cumulative and annual traffic loads (tonnage). MOVE then automatically selects an applicable strategy from a predefined set of around 10 M&R strategies, which also include the clustering of renewals on adjacent track sections. Finally, life-cycle costs are calculated for the entire network at an interest rate of 4%; costs of traffic disruption are not included. Parameters are calibrated by using an SNCF database containing detailed data on annual renewal quantities and costs. MOVE is used for presenting the long-range impacts of different M&R policies, such as postponing the renewal of tracks with timber sleepers, as well as for comparing specific renewal proposals from the SNCF maintenance regions to national averages.

Danzer [2001; 2004] developed a model, named LCCRailTrack, which estimates life-cycle costs for tracks and switches depending on an operating environment defined by the user. The model provides deterioration functions based on a Markov multi-state model. The possible states of a railway track, as well as the chances of changing from each state to a worse deterioration state, need to be estimated by users; a disadvantage may be that Markov models do not take the history of the track segments into account. Danzer uses fuzzy logic to deal with the uncertainties involved in the estimation. The model was developed in cooperation with Deutsche Bahn (DB). Yet another DB model estimates the life-cycle costs of ballasted and slabs tracks (including civil substructure) on the basis of the given geographic terrain [Baumann, 2003].

ProRail has developed several models; apart from the general-purpose LCC Calculation Tool (see Section 2.3.1), a tool named Optimiser Plus is used at a central level to develop strategic maintenance concepts for line sections, which are to be optimised in terms of life-cycle costs and RAMS risks. The Optimiser Plus uses data that is included in maintenance concepts of individual types of assets. The idea is to find ‘optimal’ strategies for maintaining an entire railway line (section), given the specific constraints and aims (e.g. availability and reliability) for that line; input is based on assumptions regarding the impact of maintenance interventions (on lifespans). The first project was an analysis for the HSL South project [Baas and Roost, 2000]. With this approach, it should eventually be possible to ‘translate’ the performance regime into practical maintenance strategies for specific line sections. Problems to be dealt with include, however, the lack of empirical data, technical staff experiencing the concepts as a threat, and existing regulations for M&R [Slump, 2003].

The QM4C Model is used in ProRail for strategic studies and cost control in the OPC maintenance contracts. QM4C estimates life-cycle costs on the basis of general characteristics of the line (section) under consideration [Swier, 2004]. Again, the HSL South project was the trigger for the model development. In contrast to tools such as TRACS, QM4C is not based on degradation models, but on historic cost and performance data from existing railway networks, which are aggregated to the level of different types of assets. The model is based on a couple of reference cost and availability templates, which contain data on over 100 infrastructure components (e.g. switches and track systems) from the Dutch rail network. This

26 TETRAS is another DB model, which seems able to handle degradation modelling.
27 An asset maintenance concept is meant to contain all key data of a particular asset type, needed to develop maintenance strategies for assets of that type in relation to the entire rail infrastructure on a line (average lifespan, M&R activities and frequencies, mean time between failures, mean time to repair, unit maintenance costs etc. [ProRail, 2000c].
data relates, for example, to population quantities and numbers, unit costs for construction and M&R, average economic service lifetimes, and average downtimes. Around 400 cost norms explain ProRail’s annual M&R costs of approximately €400 million. Because these templates reflect the particular Dutch situation in terms of train intensities, reliability standards, possession regimes and wages, a cost index model is used to extrapolate the data to changed operating environments or even entire new lines, such as the HSL South. This index model was derived from the international UIC InfraCost study.

Researchers from a range of European countries, including Putallaz [2003], Girardi [2003], Steinegger [2003], Saccardi [2003], and Vatn [2003], recently reported the development of LCC tools for their national IMs. Most attempt to include, in various levels of detail, estimates of traffic disruption costs caused by the infrastructure. Many publications referred to do not describe the structure of such systems or details of application, possibly because this is considered proprietary to the respective railways. The model of Putallaz is particularly interesting. It uses statistical analysis on the basis of historic M&R work logs and indicates the impact of maintenance on the availability of future line capacity (for traffic).

Estimating and minimising traffic disruption can be considered a special area of LCC research, requiring mathematical algorithms or simulation models. Studies that have been undertaken over the last few years include attempts to develop:

- optimal maintenance execution plans, i.e. scheduling consecutive M&R machine runs optimally in time, in order to minimise integrated costs of track works [Siefer, 1998];
- optimal possession allocations over the network for mainly minor M&R works, which are performed during the train timetable, in order to minimise disruption [Lake et al, 2002];
- optimal clustering and timing of minor M&R works into regular, mostly nightly, maintenance slots [Budai, 2004];
- review procedures for track layouts such as in [Gallmann et al, 2004]; this study combines LCC with mathematical algorithms to simulate the traffic impacts with and without disruption switches.

The aforementioned studies are believed to describe the current state of the art in rail-infrastructure-related LCC research. In addition to the railway-initiated or university-driven LCC work, consultants and (associations of) railway suppliers provide also more and more LCC services. Most of the discussed efforts relate to track, but efforts are also being made with respect to power supply and signalling, e.g. point machines, level-crossing equipment and interlockings. The focus in that field is on condition monitoring and developing more reliable equipment [Olivierse, 2002]. An issue here is that there is already an installed base of equipment, supported by a certain provider, and introducing new equipment often implies that maintenance staff need training, which raises the costs of investment.

All in all, LCC is proving to be an area of increasing interest, but with little standardisation yet in procedures, data and tools. ImproveRail, an EU-funded research project, was a first attempt to come to a more standardised methodology [ImproveRail WP6, 2001]. However results do not seem to be widely distributed as yet. The remaining part of this book describes the LCC-based approach that has been developed and applied by the author; publications on the research and the DSS used, named LifecycleCostPlan, have been made since 1998 [see Zoeteman, 1998, 1999, 2001 etc.].
2.4 Conclusion: a desire for performance-based management

This chapter provided an extensive overview of (a) changing conditions, faced by railways and separated IMs, and (b) technological and managerial developments in the fields of railway engineering and maintenance. Table 2.1 summarises the discussed trends and specific R&D and 'management change' programmes.

It can be concluded from Table 2.1 that railway IMs and suppliers in the discussed countries face increasing performance demands, contractual obligations and work restrictions. Their responses have so far been characterised by reorganisations aimed at improving responsiveness to these demands (e.g. decentralisation), and change projects, in order to create systematic, output-driven processes. There are also expectations from the introduction of computerised tools for analysis and planning of maintenance, although many are in a preliminary or prototype phase. A process to plan infrastructure performance is apparently looked for, which starts from desired levels of infrastructure functionality and performance. On the next page this desired way of working is roughly outlined in a process scheme, using the suggested process set-up of European Standard 50126 and the set-up of the tendering process for the Dutch high-speed line [CENELEC, 1999; HSL P.O., 1999].

<table>
<thead>
<tr>
<th>Table 2.1: Re-engineering railway design and maintenance practices</th>
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<tr>
<td><strong>Typical new conditions for rail infrastructure managers</strong></td>
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<tr>
<td><strong>System configuration</strong></td>
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<td>- Infrastructure separation</td>
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<td>- Outsourced maintenance</td>
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<td>- Infrastructure charging requirements</td>
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<td>- Performance regimes</td>
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<td><strong>Operating environment</strong></td>
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<td>- More diverse transport mix</td>
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<td>- Higher traffic densities</td>
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<td>- Focus on punctuality</td>
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<td>- Longer operating hours</td>
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<td>- Desire for more functionality</td>
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<td><strong>Infrastructure policy</strong></td>
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<td>- Stricter health and labour safety legislation</td>
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<td>- Fluctuating M&amp;R budgets</td>
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<td>- Interoperability agreements</td>
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<td>- Environmental constraints</td>
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| **Typical management change and R&D programmes**                 |
| **Organisation, contracting**                                    |
| - Decentralising organisation                                    |
| - Developing internal management contracts                       |
| - Life-cycle cost analysis obligations for staff                 |
| - Developing output-driven contracts (ENS0126) and quality control systems |
| **Technology, work methods**                                     |
| - 'Industrialising' M&R work, mechanisation                      |
| - Digital scouting and condition monitoring                      |
| - Developing improved infrastructure components                   |
| - Clustering maintenance in planned rosters                      |
| **Management information**                                       |
| - Developing (strategic) maintenance concepts                    |
| - Developing computerised asset registers and M&R planning systems |
| - Life-cycle costing studies                                     |
| - Benchmarking studies                                           |

| **Typical stated goals of the management change and R&D programmes: realising...** |
| **Quality of design and maintenance strategies**                 |
| - Improved quality of the infrastructure                         |
| - Increased RAMSHE                                              |
| - Reduction of maintenance needs                                 |
| - Ability of situation/asset specific costing                   |
| - Levelled and optimally used maintenance budgets and resource needs |
| - Cost-effective design and M&R decisions                       |
| **Quality of decision-making process**                           |
| - Uniform and transparent decision process                       |
| - Timely information on M&R implications                         |
| - Optimal use of expertise                                       |
| - Availability of an empirical decision basis                    |
| - Incorporation of future M&R in decisions                      |
| - Increased knowledge of (future) M&R impacts at all management levels |
In a first step, performance levels are looked for that satisfy the demands and wishes by key stakeholders and customers (e.g. punctuality aims of TOCs), shareholders (e.g. growth in operating income) and investors (e.g. accessibility of urban areas), whilst balancing them with factors such as available funding and technology. For example, it is technologically more difficult, and thus costly, to upgrade existing lines to higher levels of availability and reliability, compared to newly planned lines, because the upgrading needs to be done while ‘the house stays open’, i.e. allowing traffic to continue as much as possible. This step results in functional specifications.

Two subsequent steps are an elaboration of these specifications in terms of feasible solutions and an evaluation of the expected impacts of these solutions with respect to the desired functional specifications. For this purpose, reliability and cost features of available technology and work methods are studied in detail and are used to elaborate comprehensive design solutions or preservation strategies for the expected financing, construction and operating conditions. These steps result in two ‘products’ (feedback) on the feasibility of the desired, functional specifications and a shortlist of feasible courses of action, which have been quantitatively assessed on their costs and service level expectations over a long timespan (e.g. life-cycle costs, maintenance needs, inherent failure levels and risks). It is still possible to modify functional specifications and rework developed solutions.

In a fourth step, a choice is made to implement a specific design and/or preservation solution on the basis of the risk preferences made by the infrastructure owner and, possibly, its lenders. This step also includes a final allocation of some well-defined risks among the stakeholders. Having made this choice, the design and preservation solution(s) can be engineered in detail, which results in a specific building plan and maintenance concepts for each individual asset and subsystem, including logistic support resources. Details of the solutions can still be modified. Figure 2.18 (on the next page) summarises this desired process, which works from a strategic towards a tactical level of decision-making.

Because the process starts from functional instead of technical specifications, the system requirements are developed top-down, from a rough, strategic level towards a detailed, technical level. Several feedback loops are possible in this process, enabling a concurrent engineering process during the conceptual design phase; in such a process, engineering steps necessary for each subsystem take place, more or less, simultaneously [Blanchard and Fabrycky, 1998]. In contrast to only designing a particular, technically feasible subsystem, this process already includes an analysis of system-wide consequences of such a design; the overall system design and maintenance strategy can be improved using the aforementioned feedback loops. What has not been discussed yet is the operational decision-making level, in which implemented solutions are used in practice. The organisation of an explicit ‘monitoring process’ during the operational state is a necessary condition for sustained application and improvement in this way of working (e.g. for collecting the necessary empirical data). This is why a so-called ‘cradle to grave’ view is necessary on the system design and use.
Figure 2.18: A decision-making process for performance-based railway design and M&R
Returning to the current state of the art in the railway sector, the picture proves to be fragmented. Despite an apparent desire for a performance-based infrastructure management process, we found that many mentioned R&D and ‘management change’ projects, especially in Europe, were initiated only a couple of years ago.\textsuperscript{28} With regard to technology, considerable achievements seem to be realised in terms of maintenance productivity and more reliable components. The management and maintenance planning process on the IM ‘shop floor’ is, however, still at a very early stage; the IMs often still have poor quantitative insight in the effects of design and M&R strategies on infrastructure performance. Most of the efforts seem to be long-range change programmes and have seen few imminent breakthroughs. This is particularly demonstrated by problems in developing and using asset information and management systems and costing frameworks based on the life-cycle impacts of decisions. Further, it proves still to be difficult to introduce performance requirements in developments, such as maintenance outsourcing and ‘infrastructure charging’. This is also due to the lacking quantitative insight at the IMs and the rail infrastructure sector in general.\textsuperscript{29}

As argued in Chapter 1, the absence of tools, procedures and skills for performance-based maintenance management could possibly lead to \textit{shortsighted behaviour} within and among the increasing number of parties responsible for parts of the railway system, at the cost of customers and taxpayers. This was the main reason for investigating how such a \textit{‘design process’} for railway design and maintenance, as depicted in Figure 2.18, can be supported as much as possible under the current management conditions. The next research step therefore consisted of a study into the maintenance literature in order to search for concepts and methods, which can assist life-cycle-based railway design and maintenance. Chapter 3 documents the first part of this research step, which concerned the search for concepts and methods in the maintenance management literature.

\textsuperscript{28} The problem statements formulated on the websites of Committees A2M06 (Railway Maintenance) and A2M01 (Track Design) of the US Transport Research Board confirm that this description of the current state of the art is up to date [TRB, 2004].

\textsuperscript{29} Trescher [2004] even notes that many recent acquisition projects seem, again, to “leave out” LCC requirements.
3. Asset Life-Cycle Management: Principles

This chapter and the next chapter together answer the second research question: *How can a life-cycle-based approach to railway design and preservation be stimulated in today's railway environment, from a theoretical point of view?* This chapter aims to identify usable theoretical concepts and methods in the maintenance engineering literature; Chapter 4 explores how these concepts fit into an approach to support decision-making in the European rail sector. Section 1 introduces the general role and importance of maintenance as a management area. Section 2 discusses the basics of maintenance engineering. Section 3 introduces asset life-cycle management (LCM), which is mentioned in the literature as being the most advanced approach to managing technical systems. Section 4 introduces and compares seven ‘sources of inspiration’ for LCM. Finally, Section 5 introduces the technique of life-cycle costing (LCC) in detail. Section 6 contains a summary and an outlook of possible functions for LCC.

3.1 Introduction

Maintenance can be defined as the combination of all technical and administrative actions, including supervising actions, to retain a technical system in, or restore it to, a state in which it can perform a required function [Dhillon, 2002]. It has a number of crucial contributions to the correct functioning of production facilities, which are summarised by Edwards and Salisbury [2003] as:

- reducing the risk of failure;
- identifying hidden or latent failures;
- extending asset life;
- improving the operating efficiency of the asset;
- reducing operating costs;
- improving the company’s image; and,
- complying with legislation.

Maintenance has long been a neglected business area, compared to areas such as production, sales and marketing, finance and logistics [Vonk and Smit, 1986]. It largely remained an ‘operational art’ performed by skill-based staff who were trained in the field [Wilson, 1999]; performance reporting with respect to maintenance was often limited to a minimal budget reporting [Pintelon and Van Puyvelde, 1997], and maintenance was almost
ignored in new design and installations [Smit, 2004]. A probable reason is that maintenance is always a secondary, supporting process to enable optimal equipment conditions for the other business functions. The merits and shortcomings of the service rendered are not directly apparent [Pintelon et al., 1997]; Dekker [1996] adds: ‘It is very easy to quantify direct maintenance costs, but very difficult and sometimes subjective to quantify the benefits of maintenance’.

However, over the past two decades, the importance of maintenance, both in controlling operating costs and for a correctly functioning production process, is rapidly becoming more recognised. A number of developments are responsible for this situation. Firstly, maintenance has proven to be an area where costs tend to increase, ‘without much grip from higher management’ [Dekker and Soares, 1996]. Dekker and Van Noortwijk [2001] mention that maintenance expenditures generally increase faster than average price inflation. Duijvenvoorden and Verdoes [1993] estimated that maintenance services amounted in 1993, even then, 10% of the Dutch national income. Cost levels for maintenance are particularly high in a number of capital-intensive sectors, such as mining, oil refineries, and civil structures, offshore platforms, buildings, dykes, roads, railways and bridges [Dekker, 1996]. The largest maintenance departments and companies can also be found in these sectors. As an example, maintenance departments in chemical plants account for around 30% of the total manpower [Pieri et al., 2002]. These cost increases are becoming problematic in most developed countries, where the costs of infrastructure are increasing faster than available government budgets (because of the increasing age of the infrastructure). Jaarsma and Van Dijk [2001] mention that road maintenance expenditures now exceed 50% of the total expenditures for road infrastructure. It is gradually recognised that appropriate maintenance should be provided in order to preserve the civil infrastructure systems, because they represent such a large amount of the national property. This is, for instance, demonstrated with the adoption of the Intermodal Surface Transportation Efficiency Act in the USA in 1991 and GASB Statement 34, which requires agencies to include the value of their infrastructural assets on their balance sheets [Wittwer et al., 2002; Maze and Smadi, 2003]; ‘Public sector agencies are required to shift their focus from capacity expansion to the preservation and operation of the $1 trillion investment in highways and bridges’ [Switzer and McNeal, 2004].

In addition to growing cost levels, the impacts of inappropriate M&R or ‘design for maintenance’ on system reliability and availability are also increasingly recognised. Indirect costs can be loss of production, delay in contractual fulfilment, loss of confidence of valued customers, loss of man-hours and social costs (e.g. accidents). Firstly, production systems have become larger and more complex; production control has become more refined over the years, and, in the event of breakdowns, these systems are not easily repaired [Gits, 1992]. Blanchard [1997] states that the costs of lost production can therefore be 2-15 times the maintenance costs. Kobbacy [1992] points to a study that could directly explain the low productivity of British industry, compared to German plants, as poor maintenance: ‘Although the machinery in British plants was not older, the breakdowns were more frequent and lasted longer’. Secondly, time-sensitivity of production has increased across practically all sectors, due to the introduction of just-in-time (JIT) concepts and higher expectations from customers [Muilerman, 2001]. Capacity demands of most production and infrastructure systems have increased because of JIT and growing demands, while inventory levels are minimised.
Flexibility in the event of breakdowns is reduced and breakdowns can rapidly affect the entire value chain, which is why proactive maintenance policies are needed [Jonsson, 1997].

A final cause for the attention to maintenance management is the downsizing of maintenance departments and the outsourcing of specific tasks or larger parts of the maintenance process to external parties. According to Dekker [1996], this necessitates decisions to be defended in an objective and quantitative way.

The recognition that maintenance needs careful planning has, apparently, resulted in a relatively extensive body of knowledge on maintenance management; several authors distinguish phases in the development of the maintenance function in a production company, depending on how intensively this knowledge is used [Van Duijvenvoorden and Verdoes, 1993; Vonk and Smit, 1996; Fernandez et al., 2003]. Three stages can be identified. In the first phase of operational maintenance management, a company focuses on minimising direct maintenance costs through an efficient use of maintenance resources and materials. A result of this phase is an information system to improve maintenance processes. In the maintenance-engineering phase, management starts to focus on minimising both maintenance and maintenance-dependent costs. A systematic analysis of failures is used to revise maintenance strategies in order to improve reliability; aggregated data on the degradation behaviour of assets is collected. In the third phase, an LCM approach is introduced which aims to minimise life-cycle costs. Figure 3.1 on the next page shows the sources of these life-cycle costs. In order to minimise life-cycle costs, system behaviour and maintenance actions need to be known and optimised right from the initial design phase for new equipment.

The following section introduces the basics of managing maintenance, from an engineering perspective. Subsequently, Sections 3 and 4 discuss the state of the art.

3.2 Maintenance engineering basics

Maintenance management is defined as the ‘art’ of carrying out the right maintenance tasks at the right time and in the most effective way [Wilson, 1999]. The main starting point is the necessity of managing and reducing the number of failures and reactive maintenance. Corrective maintenance may result in the lowest direct maintenance costs, but is also the highest loss-making item in a company because of reduced quality and reliability, not to mention safety [Wilson, 1999]. A failure requires much more repair time than the normal repair time. Time is spent on locating people, finding out the cause of the failure, collecting the spare parts required and carrying out the actual repair work. Timely inspection and maintenance work means that potential failures can be identified and avoided; preventive maintenance strategies can therefore be highly ‘profitable’.

On the other hand, planned maintenance is also disruptive when it cannot be performed ‘after-hours’, i.e. in non-operative time. In that case, a system breakdown still results, although better measures can be taken to reduce the negative impacts (see Figure 3.2 on the next page). The ultimate aim of maintenance management is to guarantee a defined level of operational reliability, while controlling the costs and planned time involved in performing the maintenance. Wireman [1998] adds that maintenance management should
result in 'maximising the return on investment of the asset'. This implies that, from time to time, proactive decisions must be made in order to control maintenance cost levels, because systems usually degrade over time (see Figure 3.3).

Figure 3.1: System life cycle and life-cycle costs [Mishalani and Olayé, 1999, modified]

Figure 3.2: A breakdown of operating time into time elements [Wilson, 1999]
Figure 3.3: Characteristic of a proactive approach [Wilson, 1999, File, 1991]

A proactive approach needs a consistent set of asset (maintenance) strategies that determine the appropriate tasks and activities needed, in relation to the importance of the particular asset within the total production system [Wilson, 1999]. The maintenance manager is responsible for the measurement of and timely interference in the degradation process of these individual components. A first effort is therefore to gain a good understanding of quality degradation patterns.

After their installation, assets degrade depending on time and usage (e.g. ‘wear and tear’ due to contact forces between rail and wheels). A well-known concept from the maintenance literature is the bathtub curve shown in Figure 3.4, which shows the chance of failure over time. After installing a new system, the first phase is one of infant mortality, with many teething problems. Next, the system reaches its steady-state, with mostly random failures. In the last phase, the failure rate increases again as the system becomes obsolete. The exact form of the failure pattern is thus composed of the rates of ‘wear-in’, random, and ‘wear-out’ failures. The Weibull distribution is generally considered to be an appropriate distribution to model these failure rates over time [see Cox, 1991]. For many modern systems, the bathtub curve generally seems to have a theoretical rather than practical value. For example, File [1991] mentions that the majority of failures in well-designed and manufactured equipment are random.

Figure 3.4: Theoretical failure probability over lifetime [cf. Huijben, 2001]
Knowing the failure probability over the lifetime of the equipment provides a first, important insight for the purpose of planning renewals but is generally insufficient for maintenance management; more insight is needed into the conditions causing failures. The occurrence of failures may be random with respect to calendar time or age, but they are still the logical result of a non-random timescale or usage factor [Woodhouse, 2001]. Fortunately, this condition is often (directly or indirectly) measurable, which can allow the development of balanced, condition-based asset maintenance strategies. Figure 3.5 shows typical degradation patterns found in practice; these can succeed each other over time for a single asset. The instantaneous degradation pattern should only be allowed in the design of an asset if it does not lead to important safety-related risks, environmental problems or production loss; only the ‘graceful’, gradual degradation patterns enable the maintenance manager to timely measure the degrading condition and perform necessary maintenance.

![Degradation Patterns](image)

**Figure 3.5: Typical degradation patterns**

The definition of a failure needs some elaboration. A failure occurs when the loss of function of an asset, due to degradation, passes a certain quality standard or threshold. A distinction can be made in total, functional and potential failures (see Fig. 3.6). A total failure occurs when the equipment has suffered a total loss of function and is not available for use. Major breakdown or corrective maintenance is needed and, if an incident in the operations was caused, a disaster recovery process has to be initiated. If an incident has not yet occurred emergency work orders are given to prevent such and to start the corrective maintenance quickly. A functional failure occurs when a safety or operational quality standard is passed. Functionality is impaired but the equipment can still be used at a lower production rate (e.g. speed restriction). A temporary measure might be required and minor corrective maintenance is needed to restore the system to the desired quality. A potential failure is detected when a warning standard has been passed. Although the desired function of the equipment is not yet affected, specific preventive maintenance activities have to be performed in time to restore the quality, i.e. within the so-called P-F interval where P stands for potential failure and F for functional failure. Even though the warning standard has not been reached yet, preventive maintenance can still be cost-effective when it extends the asset life. In many cases, however, too much maintenance can also be harmful; an example is that railway track tamping also leads to degradation of the ballast bed, which will, in the end, worsen geometric and structural quality.
Figure 3.6: The asset degradation process [Wilson, 1999]

The maintenance manager will develop the asset maintenance strategy on the basis of the degradation patterns of the (components of the) asset, probability of failure, the possible maintenance interventions, and the criticality of failure for the overall production system. Moreover, individual asset strategies will have to be coordinated with each other; the assets in the production system are economically, structurally and stochastically interdependent [Plasmeijer, 1999]. This is because economies-of-scale are involved (unit costs) and because degradation in one asset often means an increased likelihood of degradation in technically related assets. All in all, it can therefore be stated that maintenance managers of complex production systems face the difficulty that they have to monitor a variety of assets with different properties, conditions and multiple-damage features. In addition, they can choose a variety of maintenance types that result in different condition improvements and which tend to have economies-of-scale.

A coherent framework, or maintenance concept, is needed to govern all different condition-based strategies, also because of the long-term character of many maintenance impacts. Plasmeijer [1999] notes: ‘maintenance planners consider a finite planning horizon, in which the long-term consequences are not easily contemplated’. Developing such concepts has become a key challenge in managing and engineering maintenance [see Geraerds, 1992; Gits, 1992; Waeyenbergh and Pintelon, 1992]. The concepts can be very basic or very detailed and advanced, depending on the complexity of the system and the operating environment. This is why Organ et al. [1997] call maintenance management ‘an empirical rather than an analytic science; the model required to predict the maintenance requirements of a plant is at least as complex as the plant itself’.

Figure 3.7 shows a phased development process for a maintenance concept, describing required maintenance activities, estimated frequencies and condition thresholds, and rules for clustering activities in time and space.
The first step in developing the maintenance concept is the generation of maintenance tasks. The selected maintenance strategies define when what types of maintenance have to be performed. A distinction can be made between preventive and corrective strategies. Within preventive strategies, a further distinction can be made in calendar-based, use-based and condition-based strategies. Condition-based M&R requires a more costly organisation, because degradation processes have to be closely monitored through frequent inspections or monitoring devices. However, this can result in higher reliability and availability and cost savings; maintenance is only performed when it is really needed. For simpler calendar-based and use-based maintenance tasks, insight into the time between failures and the equipment history is sufficient (e.g. accumulated tonnage since the last rail replacement). A conservative maintenance threshold is set on the basis of a failure probability calculation.

The second step in developing a maintenance concept consists of defining clustering rules in order to create optimal work packages. For example, combined replacement of adjacent, similar components of assets can result in reduced unit costs and time per asset. This scale effect has to be balanced against the cost and time impacts of departing from the optimal frequency of the individual activities [Dijkhuizen and Van Harten, 2001]. A railway application is to harmonise renewals of rails, sleepers and ballast under certain conditions.

The third and last step is the definition of rules for assigning time windows to the maintenance packages. These windows make it possible to spread workloads and to cluster
activities dynamically on the basis of opportunities that occur in the medium and short term. The objective is to fit maintenance better into the production planning. Again, a trade-off is made between cost and time impacts of departing from the optimal frequency of the individual maintenance activities and the lower planning and possession costs. Scientific approaches are rarely available; a complication is that the production planning is usually strictly time-based, whereas a large part of the maintenance package is based on usage or condition [Dijkhuizen and Van Harten, 2001]. They describe an airplane maintenance application.

Once the maintenance concept is available, it becomes the centrepiece in the planning and control of maintenance (see Figure 3.8; notice that the assets are referred to here as ‘production resources’). Actual demands for maintenance tasks are generated on the basis of the concept and the realised production plan. During the maintenance process, the maintenance manager needs (to a certain degree) to constantly monitor effectiveness of the strategies and changes in the operational, financial and legal environment. Figure 3.8 depicts this process.

![Diagram of maintenance management cycle](image)

**Figure 3.8: Maintenance management cycle [Van Duijvenvoorden and Verdoes, 1993, simplified]**

### 3.3 Asset life-cycle management

Over the last decades, (increasing) attention has been paid to the maintenance literature to the management of the entire life cycle of production assets; this is reflected in the emergence of terms such as ‘terotechnology’, ‘life-cycle management’ and ‘capital asset management’. There seem not to be significant differences in the meaning of these terms (see Box 3.1 on the next page for some definitions). Irrespective of the precise definition, the underlying idea is always that impacts on system costs of ownership and performance during all life-cycle phases are already incorporated into the system design and in the development of preventative asset maintenance and support strategies.
Box 3.1: Some definitions of asset (life-cycle) management

- 'Terotechnology is a branch of technology that utilises management, financial, and engineering expertise in the installation and efficient operation and maintenance of equipment and machinery' [HarperCollins Publishers, 2000].
- 'Life-cycle management (LCM) is a method in which the decision making for the development, construction, M&R of infrastructure is focused on selecting the decision alternative, which realises minimal total life-cycle costs for the requested performance' [ProRail/RIB, 1998].
- 'LCM, with its toolbox and decision-oriented goals, seeks to render sustainability accessible, quantifiable and operational' [Rebirzer and Hunkeler, 2003].
- 'Asset management is the process of guiding acquisition, use and disposal of assets to make the most of their service delivery potential and manage the related risks and costs over their entire life' [Government of Victoria, Australia, 1995].
- 'Capital asset management is a coordinated management of the design, procurement, use and maintenance of a company’s fixed assets, in order to maximise the contributions of a companies profit over the life cycle of those assets' [Waeyenbergh and Pintelon, 1992].
- 'Asset management is the set of disciplines, methods, procedures and tools to optimise the whole life business impact of costs, performance and risk exposures (which are associated with the availability, efficiency, quality, longevity and regulatory, safety and environmental compliance) of the company’s physical assets' [Woodhouse, 2001].
- 'Transportation asset management (TAM) is a systematic process of operating, maintaining and upgrading physical assets cost-effectively. It combines engineering and mathematical analyses with sound business practice and economic theory. TAM explicitly addresses the need to integrate decisions made across all modal programme areas' [Bittner and Rosen, 2004].
- 'AM is a business process and a decision-making framework that covers an extended time horizon, draws from economics as well as engineering, and considers a broad range of assets. The asset management approach incorporates the economic assessment of trade-offs among alternative investment options and uses this information to help make cost-effective investment decisions' [US Federal Highway Authority, 2003].
- 'Asset management is driven by explicit policy goals and orientation on customer needs. It adopts a long-term view of facility condition, performance and cost. It considers options or alternatives in projects or services. Decisions on alternative investments or courses of action are based on relative merit. Tradeoffs among alternatives are explicitly considered in terms of performance and cost. Performance measures provide feedback on the effectiveness of the transportation investments and services, and management accountability for work accomplished. Objective information of high quality is applied at each step' [Neumann and Markov, 2004].

The trend in maintenance engineering to consider all life-cycle phases can possibly be traced back to the emergence of the systems engineering (SE) discipline in the last three decades, which tries to reverse the trend of separation in complex production systems [Blanchard and Fabrycky, 1998]. SE aims to systematically develop and maintain production systems according to a defined level of functionality, including maintenance performance (RAMS). Explicit design reviews or verifications have to demonstrate that decisions in every step in the design and commissioning of systems comply to specified functionality requirements for the overall system; this requires that the life-cycle performance of all subsystems – manufacturing, operations and disposal – is ‘engineered’ concurrently. Using SE, the specifications for the system and its components are deduced top-down from global functional requirements to technical specifications and drawings [INCOSE, 2003].

The emergence of SE is based on the realisation that system performance is often sub-optimal in terms of costs and performance, because subsystems and their interfaces were not

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30 The latest standard, ISO15288, also describes the required ‘enterprise processes’ needed to manage this SE process; this includes acquisition, investment and quality management processes.
well designed with regard to system properties such as: RAMS; usability (human factors); supportability (logistics); producibility and disposability; and affordability (life-cycle costs) [Blanchard and Fabrycky, 1998]. It is also based on the 'theory of committed life-cycle costs', i.e. changing system properties becomes increasingly difficult and costly in subsequent life-cycle phases and, in fact, most design and (preventative) maintenance choices are irreversible. At the same time, in many systems (a) the larger part of the life-cycle costs (typically 50-75%) is already committed as a result of design choices [see Blanchard and Fabrycky, 1998], and (b) the initial quality level after construction has a dominant influence on degradation levels [see Mishalani and Olayé, 1999]. Figure 3.9 represents this theory graphically, and shows the course of the committed expenditures versus the out-of-pocket expenditures over the life cycle. The broken line shows the influence of the asset owner on these costs, which obviously mirrors the committed cost line.

![Figure 3.9: Illustrative committed vs. real cost levels [after Hudson et al, 1997]](image)

With respect to the importance of initial quality, there are many examples. The example used here is from railway track maintenance, which has been well elaborated by Veit [2002]. He reports on an analysis of track quality data from the Austrian network, obtained between 1992 and 1999. The measurements showed, first of all, that it is impossible to override the quality of initial installation. Tamping does bring the geometric quality of the track to a much higher level, but this is always lower than the initial quality. The measurements also showed that track deterioration generally does not have a linear but progressive (exponential) character (see Formula 3.1 on the next page). These findings imply that not only will track geometry deterioration start at a lower quality level after tamping, but also that the rate of degradation after tamping will be higher than the rate of degradation after initial installation. Although this effect is minor at first, it is significant for the feasible technical, and economic, lifetime of the track, as Figure 3.10 will show on the next page. This figure is consistent with the aforementioned finding that tamping will occur with an increasing frequency in worn-out tracks; this was referred to in Section 2.3.3 as the 'memory of railway track'.
\[ Q(t) = Q_0 \cdot e^{bt} \]  \hspace{1cm} (3.1)

where \( Q(t) \) is the track roughness, \( b \) is a constant parameter, and \( t \) is the elapsing time.

![Figure 3.10: Saw-tooth pattern for geometric alignment of railway tracks [Velt, 2002]. Vertical axis represents track quality; horizontal axis represents track age.](image)

Although 'good maintenance practices have an effect similar to that of quality assurance during construction' [Kirk and Dell'Isola, 1995], it can be concluded from the above that: the sooner the correct strategies are applied, the higher the positive impact on the life-cycle costs. Van der Mooren [1987] lists 10 ways for improving maintainability ('design for maintenance') and reducing the needs for maintenance ('design-out maintenance'):

1. **Simplify the structure of the system**: e.g. reduce the number of assets, subsystems and components.
2. **Use standardised components on a company level**, which comply with international production standards (also considering the spare parts stock).
3. **Improve the accessibility of the asset, subsystems and components**.
4. **Improve the replaceability of the components** through, for example, quick assembly and disassembly times.
5. **Create a modular system design**. The disadvantages of extra connections between the modules should be traded-off against reliable connections within the modules and reduced downtimes thanks to 'repair by replacement' of a whole module (e.g. using rotables, i.e. 'assemblies that can be taken out of a technical system and can be built in again after restoring them to the operable state' [Geraerdts, 1992]).
6. **Improve the insensitivity to human failures**. Make a 'fool-proof' design for both operating and maintenance tasks and reduce required preventive maintenance.
7. Improve the insensitivity to overloading and damage. Solutions are to design fail-safe systems, reduce mechanical contact areas, install redundant systems and warning systems to reduce failure consequences.

8. Improve the detectability of the condition of critical components, not only for inspection during standstill but especially during operations; e.g. install devices for continuous condition monitoring.

9. Provide a maintenance manual to users or maintenance staff. This should describe a clear maintenance programme, i.e. maintenance concept.

10. In taking these measures, minimise the overall costs of investment, maintenance, operation, modification or upgrading, demolition and lost revenue.

Asset life-cycle management (LCM) requires a quantitative analysis of costs of ownership and operation, in order to be able to select cost-effective 'design for maintenance' and design-out maintenance strategies. Figures 3.11 and 3.12 present the previously discussed relationships between quality and life-cycle costs. Figure 3.11 shows the influence of the initial quality of the system, while Figure 3.12 shows the theoretical influence of preventive inspection and maintenance intervals. As can be seen, a law of increasing and diminishing returns will apply to investments in initial quality and preventive maintenance. When more is invested in better quality, life-cycle costs will reduce rapidly, other conditions being equal. At a certain level of quality, increased investment is needed to realise an even higher quality level, while this is not fully rewarded by reduced operating costs or higher revenues.

It is worth mentioning here that the focus in the above has been entirely on maintenance; although this is often correct for the civil infrastructure sector, where maintenance-related costs determine the ‘downstream costs’ [Dekker and Van Noortwijk, 2001], this focus is too narrow for LCM in many other sectors. LCM concerns all cost drivers and performance killers in the operation (see Figure 3.13 on the next page).

![Figure 3.11: Life-cycle costs in relation to the planned maintenance interval [Wilson, 1999, p. 64]](image-url)
Figure 3.12: Life-cycle costs in relation to designed quality/availability [File, 1991, p. 82]

Figure 3.13: Iceberg ahead! [see Flanagan and Norman, 1983]
An issue that needs to be resolved when deploying LCM, is which life-cycle perspective to adopt; this determines which cost and performance impacts are included in the analysis. Emblemsvag [2003] presents possible life-cycle perspectives for a product; in this case the product would be an ‘asset’ needed in a larger production system with a life cycle of its own. Emblemsvag [2003] mentions that, if a production perspective only is taken, then a life cycle of only five stages is considered: product conception, design, product and process development, production and logistics. From the customer perspective, a life cycle includes five different stages: purchase, use, support, maintenance and disposal. Since the consumer purchase price includes the costs of the producer, the life cycle costs will be more complete in this perspective. From a societal point of view, disposal costs and external effects, such as environmental pollution, also have to be considered. Figure 3.14 shows this entire life cycle.

![Life Cycle Diagram](image)

**Figure 3.14: Product life cycle [Emblemsvag and Bras, 2000, p. 317]**

A consequential issue is the quantification of life-cycle costs [Flanagan and Norman, 1983; Emblemsvag, 2003]. Several distinctions can be made, such as the aforementioned one between initial costs (‘upfront’) and running costs (‘downstream’). A further difference can be made in the level of tangibility of the costs. **Tangible costs** are out-of-pocket expenses for labour, materials, utilities used during construction, preventive maintenance and breakdowns. **Hidden costs** are found in the overhead of the organisation, i.e. costs for monitoring, administration, planning, insurance etc. **Liability costs** are related to liabilities (e.g. penalties) for quality losses, reduced levels of safety and environmental damage; these are difficult to quantify, but can be significant. Even less tangible costs relate to the image and relationship of the company, such as customer loyalty and worker morale. Finally, there are also the externalities that are still largely paid for by the society (e.g. noise, safety and environment). Depending on the life-cycle perspective chosen, these costs need to be either included or excluded.

The adopted perspective, and thus the costs included in a life-cycle approach, will depend on the attitude of the country and industry as a whole. Emblemsvag [2003] argues that companies generally do not go beyond the four walls of their own company without serious incentives. Actually, it seems that a life-cycle approach is in many production systems still an unusual viewpoint. Acquisition, maintenance, operation and renewal are traditionally treated
as separate activities. A principal reason for this separation, also referred to as ‘silo-thinking’, is the complexity of today’s production systems; specialised organisations or company units such as constructors, owners, managers and operators are responsible for different subsystems and phases in the life cycle. Smit [2004] states, for example, that owners and operators in the civil sector are not used to managing life-cycle costs. They do not put such performance demands to their suppliers and do not have the skills to control them; project managers and engineering contractors are judged by the realisation of work within time and budget (i.e. low costs of installation or construction). As a result, subsystems were and are often managed in an autonomous, fragmented manner. Recently, a task force of the US Transport Research Board summarised the potential barriers for a life-cycle approach as follows [TRB Asset Management Task Force, 2004]:

- ‘there is no ‘champion’ to support the introduction of LCM; there are also frequent leadership changes that undermine LCM introduction;
- LCM is likely to lead to a shifting of current, ‘historical’ investment patterns, which is difficult and will evoke resistance. It also conflicts with dedicated funding and federal-aid programme structures, as used in the US transport sector;
- LCM is not (always) connected to a strong vision, lacks practical implementation steps, over-emphasises methodology and tools;
- there is a lack of pressure and incentive to change, and change management in the public sector is difficult anyway;
- the introduction of LCM requires a long timeframe to implementation, which is a problem in itself; agencies have an inability to sustain such effort over time’.

In addition, Galehouse et al. [2004] mention marketplace pressures, such as actions by suppliers to prevent the use of new designs or maintenance treatments (even including political lobbying), and difficulties in convincing other stakeholders (e.g. explaining a shift from repairing the worst pavements first to the best pavements first, through preventative maintenance). It can therefore be expected that any approach that attempts to introduce ‘life-cycle thinking’ will face hurdles. Section 3.4 continues to study which methods and techniques are available today for supporting ‘LCM-based decision-making’ and which method(s) are, probably, suitable for introducing ‘life-cycle thinking’ in the rail sector.

3.4 Sources of inspiration for a life-cycle approach

Techniques available to encourage the introduction of LCM are discussed below in seven subsections; these are compared based on their merits (Section 3.4.8). Most of the methods originate from Japan or the Anglo-Saxon world; some of them are meant for all life-cycle phases, while others are only applicable to the design or operational phase. Since many handbooks have already been published on these methods, only the general ideas, strong and weak points are discussed here.

31 It is likely that the reforms of many other infrastructure sectors cause similar fragmentation. For instance, Openshaw [2003] and Kuit [2003] state that a drive for efficiency among the new operators in the energy sector results in a lack of incentives for long-term policy and a missing overall systems view.
3.4.1 Systems engineering

SE has already been introduced in the previous section as a useful methodology for LCM. It is particularly helpful when acquiring new systems in order to guarantee a systems and life-cycle view of design and operating issues. An example is that SE pays systematic attention to integrated logistic support (ILS), i.e. parallel to designing the production system, the required equipment, spare parts, staff, training, and computer systems for (logistic) support throughout the life cycle are also designed. Following an SE approach should not only lead to a specified system cost and performance, but should also reduce overall engineering time thanks to concurrent engineering [Prasad, 1996; cited in Herder, 1999]. SE elaborates designs and maintenance strategies top-down: first functional requirements are developed, which are detailed in a number of steps and result, among other things, in required technical specifications.

European Standard 50126 describes in detail the deliverables that are expected in this process (see also Figure 3.15 on the next page) [CENELEC, 1999]:

- **Conception.** Firstly, a market analysis identifies which types of products are required and in which quantities. Studies are then required to determine feasible technologies and possible RAMS levels. Finally, physical, social, political, financial and legislative constraints need to be identified.

- **Definition of system and application conditions.** The system mission and boundaries plus operational conditions are defined. **Functional specifications** are developed for required production functions and capacities, including 'top-level' RAMS requirements, long-term operating and maintenance strategies (e.g. reference to international quality standards, and lifespan and logistic considerations), and interfaces with existing production systems. Cost considerations play an important role in developing feasible specifications; a detailed financial account is produced.

- **Conceptual design.** A first functional analysis of sub-systems is performed. Design alternatives are assessed where possible on project and safety hazards. Each technical discipline, e.g. civil, electrical and mechanical engineering, elaborates feasible design alternatives and corresponding maintenance concepts. This elaboration results in **detailed (functional) specifications** that can be used for detailed cost estimation as well as a tender of work to engineering contractors. Based on this RAMS and life-cycle cost analysis, one or more design alternatives can be selected for the detailed design phase. It is important to define system demonstration and acceptance criteria and to elaborate RAM and safety programmes in order to clarify the roles and skills of the various parties. This includes details of a failure reporting analysis and corrective action system (FRACAS) in order to monitor the system performance and a 'change request' procedure for modifications to the original design.

- **Detailed design and implementation.** The detailed design of the system and the logistic support resources needed to operate and maintain the system are performed and verified. Functional specifications for the subsystems and components are translated into **technical specifications** for the component design and materials to be used. Technical drawings and installation plans are composed. The RAM and safety programmes must be implemented in order to demonstrate and confirm that subsystems and components conform to RAMS
requirements. This includes a so-called ‘programme control’ in order to audit the programme management itself and the control of subcontractors and suppliers.

- **Manufacture, installation, validation and acceptance.** Manufacturing and installation of the components can now commence. In addition to testing functionality and RAMS (subassemblies) of the components, the specifications need to be modified to the ‘as-built’ situation. Further activities include commencing FRACAS, training maintenance staff and acquiring spare parts. A transfer protocol contains procedures for demonstrating that the system has been delivered according to the specifications; this can include a probationary period of operation.

- **Operation, maintenance, monitoring and modification.** After acceptance, the process of long-term production can commence, including ongoing maintenance, training of staff and logistic support provision (e.g. procuring spare parts). Operational performance statistics are collected, using FRACAS, and RAM data is processed in order to improve the operational process. Identified ‘performance killers’ and ‘cost drivers’ in the technical system or procedures trigger revision of maintenance procedures and design modifications. The ‘change request’ procedure controls this process, especially since changes can have significant financial consequences. Suppliers are obliged to take measures when demonstrated costs and RAMS deviate from the specified requirements.

![Figure 3.15: Systems engineering process described by European Standard 50126](image-url)
3.4.2 Total productive maintenance

A second source of inspiration for LCM can be found in the (ideas underlying) total productive maintenance (TPM), i.e. an adjunct to the well-known concept of total quality management (TQM). TQM resulted from the work of Deming, who showed the Japanese manufacturing industry how to use statistical analysis to control quality; the first handbooks on TPM appeared in the 1980s [Tajiri and Gotoh, 1992].

TPM focuses on eliminating the so-called ‘six big losses’ in the production environment: breakdowns, set-up and adjustment losses, minor stoppage, production speed losses, quality defects (in delivered products) and rework losses, and yield losses (in sold products). It is possible to include all these losses in a ratio known as overall equipment effectiveness (OEE), which expresses how well the maximum potential productivity is approached. From the TPM standpoint, minor defects are regarded as the probable cause of losses, ‘unless these defects are absolutely determined to be unrelated to losses’ [Tajiri and Gotoh, 1992]; in the perspective of traditional quality control concepts, TPM is too detailed, leading to ‘over-maintaining’. Implementation of TPM follows strict procedures consisting of six activities: elimination of the six big losses (overall activity), planned maintenance, autonomous maintenance (i.e. operators are trained to perform simple, first-line maintenance work), preventive engineering, easy-to-manufacture product design, and education [Tajiri and Gotoh, 1992]. TPM encourages staff to learn to understand the relationship between quality conditions and defects; this process is known as root-cause analysis (see Box 3.2 on the next page for an illustration). Several techniques can be used in the search for root causes, such as fishbone diagrams (see Figure 3.16), histograms and fault-trees [ISO, 2004]. Reasons for recurring defects can be: important conditions for quality are unclear, difficult to set, tending to vary, or difficult to detect or restore.

![Fishbone Diagram](image)

**Figure 3.16: An example of a rough fishbone diagram for rail weld irregularities [Zoeteman, 1998]**

TPM is a fundamentally different approach to maintaining business assets than the ‘engineering-based’ maintenance methods and tools discussed later in this section [Davis and Willmott, 1999]. The ‘quality circles’ approach is directly intended to make all personnel a
‘shareholder’ in the process and to change the culture of maintenance departments, which tend to strictly follow the suppliers’ manual. Operators and top management also take part in these ‘quality circles’. A TPM programme will only be successful after some years, and it is difficult to sustain attention [Beer, 2003].

Box 3.2: Principal ideas behind TPM and root-cause analysis [Gene Bellinger, 2003]

‘To find root causes there is only one question that’s relevant, "What can we learn from this situation?" (...) most organisations spend far more time looking for culprits than causes and because of this misdirected effort seldom really gain the benefit they could gain from understanding the foundation of the unwanted situation. Consider the following two scenarios.

Scenario no. 1
The Plant Manager walked into the pant and found oil on the floor. He called the Foreman over and told him to have maintenance clean up the oil. The next day while the Plant Manager was in the same area of the plant he found oil on the floor again; he subsequently raked the Foreman over the coals for not following his directions from the day before. His parting words were to either get the oil cleaned up or he’d find someone that would.

Scenario no. 2
The Plant Manager walked into the plant and found oil on the floor. He called the Foreman over and asked him why there was oil on the floor. The Foreman indicated that it was due to a leaky gasket in the pipe joint above. The Plant Manager then asked when the gasket had been replaced and the Foreman responded that Maintenance had installed 4 gaskets over the past few weeks and they each one seemed to leak. The Foreman also indicated that Maintenance had been talking to Purchasing about the gaskets because it seemed they were all bad. The Plant Manager then went to talk with Purchasing about the situation with the gaskets. The Purchasing Manager indicated that they had in fact received a bad batch of gaskets from the supplier. The Purchasing Manager also indicated that they had been trying for the past 2 months to try to get the supplier to make good on the last order of 5,000 gaskets that all seemed to be bad. The Plant Manager then asked the Purchasing Manager why they had purchased from this supplier if they were so disreputable and the Purchasing Manager said because they were the lowest bidder when quotes were received from various suppliers. The Plant Manager then asked the Purchasing Manager why they went with the lowest bidder and he indicated that was the direction he had received from the Vice-President of Finance. The Plant Manager then went to talk to the Vice-President of Finance about the situation. When the Plant Manager asked the VP of Finance why Purchasing had been directed to always take the lowest bidder the VP of Finance said, "Because you indicated that we had to be as cost conscious as possible!" and purchasing from the lowest bidder saves us lots of money. The Plant Manager was horrified when he realized that he was the reason there was oil on the plant floor. Bingo!

You may find scenario 2 somewhat funny, and laugh at the situation. It would be better if the situation made you weep because it is often all so true in numerous variations on the same theme. Everyone in the organisation doing their best to do the right things, and everything ends up screwed up. The root cause of this whole situation is local optimisation with no global thought involved. Scenario 2 also provides a good example of how one should proceed to do root cause analysis.’

3.4.3 Reliability analysis

A third useful area for improving maintenance management concerns reliability analysis or reliability theory. Reliability analysis is a field that emerged in the 1960s and where considerable research has been conducted; see Dhillon [2002] and Blanchard and Fabrycky [1998] for an introduction to the basic concepts. Reliability models assist in analysing the contribution of subsystems and components to the overall reliability of a production system; reliability of these components is usually taken as a black box with given failure probabilities, in contrast to the aforementioned approach of degradation modelling. Using these probabilities, it is possible to estimate reliability for each function of a technical system and
defined design alternatives (e.g. including or excluding redundant backup systems). A disadvantage is that detailed information, e.g. ‘past performance’ records, are necessary in order to develop reliable models. This is why special organisations manage reliability databases in several industrial sectors [Smit, 2004]. Reliability analysis seems especially helpful for designing complex production equipment.

3.4.4 Quality Function Deployment

A fourth, relatively little-known area of inspiration for system maintenance management is quality function deployment (QFD), which originates from Japan. QFD is a structured approach to include the ‘voice of the customer’ in the design process; customer needs or requirements are defined and translated into specific plans to meet those needs [QFD Institute, 2003; Rolstadás, 2002]. This system is different to other approaches such as TPM because, at best, they deliver problem-free systems, but cannot maximise on so-called ‘exciting product quality’. The aim is to maximise customer satisfaction, which is expressed in metrics such as return business and compliments [Mazur, 2002]. All kinds of data sources are used, such as interviews, surveys, focus groups, customer specifications, and observation.

Results are summarised in the product planning matrix or ‘house of quality’, which is used to derive requirements to lower levels, including technical quality and reliability. As an example, Dimsey and Mazur [2002] describe how QFD was used in designing a new car braking system. QFD was used to determine the various functions of the system and performance levels to users, using costing studies and an Internet-based questionnaire. They developed two alternatives: a low-cost design and a high-performance design. Emblemstvag [2003] considers it as an interesting concept that can be coupled with ‘target costing’, which means that a design process aims at specific performance/cost levels. However, he mentions that caution is needed, as QFD introduces much subjectivity in the design process. QFD is primarily meant to identify desirable performance levels or functional requirements.

3.4.5 Reliability-based inspection and maintenance concepts

A fifth area relates to reliability-based or risk-based approaches that systematically derive a set of necessary maintenance tasks. A well-known approach is reliability centred maintenance (RCM), which originates from the aviation industry. Moubray and Foltynie [1999] mention that RCM studies are used both during the design and operational phase of a system in order to develop a maintenance concept for a given design (alternative), which delivers required reliability while eliminating ineffective maintenance. They mention the questions that RCM entails:

1. What are the functions and associated performance standards of the asset?
2. In what ways does it fail to fulfil its functions?
3. What causes each functional failure?
4. What happens when each failure occurs?
5. In what way does each failure matter?
6. What can be done to predict or prevent each failure?
7. What should be done if a suitable proactive task cannot be found?
RCM provides a number of procedures and rules to answer these questions; this results in a programme of predictive, preventive, and detective maintenance tasks as well as mitigating measures needed in the event of failures. The following steps are followed:

1. Functional block diagrams are made, which show the contribution of the components and subsystems needed for the functioning of the total system.

2. On the basis of these diagrams, a failure modes and effect analysis (FMEA) is made. It enables a ‘bottom-up’ identification of possible failure modes, causes and effects. Only the maintenance-significant items (MSIs) are considered, i.e. those components having safety, operational and economic effects. The criticality of the effects is assessed in a phased fashion. First the Local Effect is assessed, i.e. the consequence at the component level. Subsequently, the Next Higher Effects (subsystem level) and End Effects (system level) are determined.

3. The FMEA worksheet is directly usable to list the required maintenance tasks (‘task analysis’). The most suitable maintenance strategies can be selected according to their effect, the detectability of the quality degradation, and the rate of degradation. The FMEA worksheet is the core of any RCM study.

4. Costs and reliability impacts of different maintenance task packages can be assessed as well as required logistic support (e.g. spare parts).

RCM emerged in the airline industry and is a structured method, well suited to complex systems with many different failure modes [Vatn et al., 1996]. However, it requires considerable resources and people because a process has to be organised, in which teams are reliably developing parts of the FMEA; team members first need a thorough training in the RCM technique. Firstly, commitment problems can occur as a result [Hansson and Backlund, 2003]. Secondly, ‘RCM provides no sound foundation for claiming that the maintenance strategy derived is in any sense “optimal” [Vatn et al., 1996]’. Woodhouse [2001] explains this as follows: ‘RCM can miss important combinational effects, as it treats all modes individually. It is reliability-centred, so it misses tasks to extend life, raise efficiency, etc.’

Another reliability-based concept comes from the petroleum industry and is called risk-based inspection (RBI). Its aim is to produce a programme that assures mechanical integrity and reliability of static systems by selecting condition monitoring (CM) equipment. RBI uses a large amount of technical data on corrosion rates, material properties and effectiveness of inspection methods. According to Woodhouse [2001], RBI is powerful in the ‘probability times consequence’ view of criticality, but again, ‘is notably weak in determining how much to spend on the inspections and in pointing to alternative risk-treatment options’.

3.4.6 Engineering economic analysis

A sixth area of inspiration for maintenance management is found in engineering economics methods that can quantify the costs and benefits of different design and maintenance solutions. A first concept, already introduced in Chapter 1, is LCC:

‘Life-cycle costing is an economic assessment of an item, system or facility and competing design alternatives considering all significant costs over the economic life, expressed in terms of equivalent currency units’ [Kirk and Dell’Isola, 1995].
Consequently, LCC is defined as [The White House, 2003]:

'The overall estimated cost for a particular (programme) alternative over the time period corresponding to the life of the programme, including direct and indirect initial costs plus any periodic or continuing costs of operation and maintenance'.

Although the basic principles of LCC were developed more than 100 years ago, systematic implementation began only 25-30 years ago [Salem et al., 2003]. Nowadays, LCC is used for several purposes. Its main application is still to serve as a tool for engineering; it is used to eliminate costs of usage in the design, development and procurement of large capital goods and open systems, i.e. 'systems that evolve over time and change with their environment' [Emblemsvag, 2003]. Recent applications include LCC being used as a cost accounting system and in environmental impact studies [Emblemsvag, 2003].

Government regulation or industry standards have been developed in several countries to stimulate LCC-based design practice. Kirk and Dell’Isola [1995] mention the first US example, concerning tractor acquisitions in 1938: ‘The General Accounting Office (GAO) supported acceptance of bids predicated on the total costs to the government after 8000 hours of operation’. Many new rulings followed in the 1970s, firstly in the military sector and then in the building industry, mainly to save energy. LCC has increasingly become a common method in the chemical, pharmaceutical, and oil industries, as well as in utility and infrastructure sectors [Waeyenbergh and Pintelon, 1992; NORSOK, 1994; Engelhardt et al., 2002; Jay and McCormick, 2002; Cowe Falls and Tyghe, 2004].

LCC studies use the fact that life-cycle costs of most technical systems comply with Pareto’s law of maldistribution, i.e. a few ‘vital’ assets or activities cause the majority, e.g. 80%, of total costs [Woodhouse, 2001; Emblemsvag, 2003]. LCC therefore starts with a 'cost breakdown' exercise in order to identify key cost drivers. The remaining analysis focuses on those drivers. LCC is appropriate in the following situations [Smit, 2004]:

1. Clients can put specific demands to the level of maintenance and maintenance-related (operating) costs. A supplier therefore has to gain insight into expected costs and performance, as a contractual agreement.
2. During the design phases, motivation is required as to whether or not to install backup systems or to use components and materials of a higher quality. Proposed design alternatives have to be assessed systematically in order to select the most cost-effective and robust solution.33
3. During the operational phase of the railway line, analysis is required as to whether or not the technical subsystems should be replaced or need modifications (economic obsolescence) or whether the maintenance concept should be improved.
4. During the operational phase of the railway line, LCC can help to identify 'performance killers' and 'cost drivers' that should be eliminated from future designs or system upgrades.

32 Kirk and Dell’Isola mention Principles of Engineering Economics, E. Grant 1930, as a first reference.
33 Kirk and Dell’Isola [1995] argue that LCC might also be useful in the ‘pre-design’ stage of project planning. They mention, as examples, an analysis of the project site conditions given the planned production function (site analysis) and, vice versa, a use analysis (given a selected site).
The literature argues that LCC is able to deliver estimates quickly that can help in selecting decision alternatives with ‘best value for money’, in contrast to other concepts. Emblemsvag [2003] adds that the performance measures of LCC fit into the managers’ ‘return-on-investment’ thinking, which is why it should be a good way to involve decision makers in the trade-offs. Kirk and Dell’Isola [1995] summarise the following strong points of LCC as:

- ‘creating cost awareness and visibility;
- providing the most appropriate yardstick for measuring the overall economy of design alternatives;
- developing data that can be valuable for future studies and that a higher authority can review to validate the selection of alternatives;
- being systematic, rational and objective and thus imparts credibility to the decision-making aspects of the design’.

However, LCC also has a number of known obstacles and weak points. Firstly, LCC requires favourable conditions for obtaining reliable input data, because consistent empirical data on capital costs, maintenance and disposal is usually missing [see El-Haram et al., 2002]. Data collection can be time-consuming, because many LCC studies go beyond traditional organisation boundaries [Kirk and Dell’Isola, 1995]. Validity of outcomes can become questionable when insufficient expertise can be mobilised. Blanchard and Fabrycky [1998, cited in Stavenuiter, 2002] mention that applying LCC in an early stage of the life cycle can lead to a complex, inexact study, but that it seems the only available approach to assess the impact of design, operation, support and disposal decisions. Emblemsvag [2003] argues that LCC, in combination with an explicit analysis of uncertainties, should be able to enhance the risk management capabilities of the decision maker, even when ‘hard’ measured data is missing. With respect to the availability of such data, Dekker and Van Noortwijk [2001] argue that the civil infrastructure sector is rather ‘lucky’. For example, roads and railway tracks degrade slower than mechanical equipment and consist of many comparable segments, i.e. duplications – this provides decision makers with more time and reliable data.

Another limitation of LCC can be that it is, in principle, cost-centred. Selected alternatives need to meet required functional specifications, such as safety, aesthetics, flexibility (expansion potential) and environmental friendliness [Kirk and Dell’Isola, 1995]. In many design and maintenance cases, it is standard practice to first develop such technically feasible, acceptable alternatives; however, there can be cases in which decision makers would like to choose between alternatives which also differ in their non-monetary ‘benefit surplus’. LCC authors usually recommend including non-monetary aspects through multi-criteria analysis or by composing an effectiveness indicator. For example, Emblemsvag [2003] discusses an approach to include system capacity and reliability in a cost-effectiveness ratio (Formulae 3.2 and 3.3; see Emblemsvag, 2003, for details).

\[
CE = \frac{E}{LCC}
\]

(3.2)

where CE = cost-effectiveness, E = effectiveness, and LCC = system life-cycle cost
\[ E = A \cdot R \cdot M \cdot \text{CAP} \] (3.3)

where \( A \) = availability, \( R \) = reliability, \( M \) = maintainability (related to repair time) and \( \text{CAP} \) = capability (ratio of actual output vs. maximum practical output of the system). \( R \) and \( M \) are both functions of time, because 'a time will come when purchasing new assets becomes less costly than maintaining old assets.'

A final drawback of LCC, as experienced by some authors, is that there is no international, cross-industry agreement on LCC. Salem et al. [2003] mention that there is 'tremendous variation in the factors included in the analysis with regard to some critical issues such as the analysis period, user costs, and service life of the infrastructure unit'. Hodges [1996] states that international, cross-industry agreement on the scope of 'what constitutes a life cycle cost' proves to be difficult, because 'the consequential costs in the event of an asset breakdown can be several times its capital value in some industries'. Arditi and Messina [1999] found in a survey that this is the second most important (stated) reason, after the lack of reliable past data, for local authorities not to use LCC.

All in all, LCC seems highly usable when starting to develop a long-term view of decision making, as is also extensively argued by Emblemsvag [2003]. It should be usable in the entire range of decisions 'from cradle to grave' (design, operation, maintenance, and disposal), although LCC handbooks primarily discuss examples from the design of new systems. Emblemsvag [2003] confirms that those few companies that actively use LCC use it for procurement and design, and rarely for end-of-life issues that emerge in a maintenance situation. Many LCC models are also financially oriented models, which lack degradation models or models to estimate operating costs, including travel time losses and emission reductions. In the field of civil engineering, there are a relatively large number of LCC studies based on detailed degradation data and probabilistic approaches [Frangopol et al., 1997; Frangopol and Furuta, 2001; Li and Vrouwenvelder, 2002; TRB, 2003]; however, they mostly apply to civil assets such as bridges and pavements and less to railways. LCC models on railway track are at a more general level (see Section 2.3.6 for examples).

A second available concept is value engineering (VE), also referred to as value analysis, value management, value control or value methodology [SAVE, 2003]. In contrast to LCC, where no serious attempts are made to challenge previously identified functional requirements, VE studies attempt to eliminate so-called non-essential functions that represent unnecessary costs. VE originated from General Electric in the 1940s and 1950s, where the Second World War had caused labour and material shortages. VE focuses entirely on construction or acquisition projects and is in fact a combination of several techniques, e.g. LCC, brainstorming and functional-block diagramming. A standard VE job plan is followed step-by-step [see Zimmermann, 1982]. The key point of VE is that a small team of individuals, who represent different disciplines and who do not have vested interests in the project, carry out the job plan [Federal Highway Administration, 2003].

\[3^4\] An interesting example of a model that includes all such impacts, a so-called full-absorption model, can be found in Hackney and De Neufville [2001].

\[3^5\] A European Standard on the application of Value Engineering, EN12973, was published in 2000.
An interesting example of how VE has penetrated current practices comes from the Federal Highway Administration, where federal, state and local agencies participate in the VE programme. Projects typically selected for VE are high-cost projects; project that ‘are just not worth the expenditure necessary to complete them’; low-priority projects that fail to meet the budget cut-off; and problematic projects. The VE teams provide as many recommendations as possible to staff and management. The teams cannot determine the projects to be selected for studying. The VE programme is considered a success; SAVE [2003] mentions that VE studies of US highway and transportation departments saved more than $800 million in 1999.

3.4.7 CMMSs and maintenance optimisation

A seventh area of inspiration concerns the development of computerised maintenance planning and optimisation tools for existing production systems. This area concerns two closely linked developments. Computerised maintenance management systems (CMMSs) aim to automate data collection and processing as well as other planning tasks (to some degree) [Wilson, 1999 p786]; they are also sometimes referred to as computer-aided maintenance management systems (CAMMs) [Llerena, 2000]. The first aim of CMMS implementation is to plan maintenance works in an objective manner, through a combination of: empirical input data; quantified criteria and objectives, such as defined damage features and LCC; and, acknowledged models for predicting quality degradation. The second aim is to plan the maintenance work as objectively as possible, but also to prioritise works as optimally as possible, regarding their economic impacts – this is where the field of optimisation, discussed below, can assist. Apart from cost savings through better planning, CMMSs are expected to ‘accelerate the otherwise slow process of pushing information up and down through maintenance and production organisation levels’ [Swanson, 2003]. This is especially important for organisations with operations covering large geographical areas, such as public utilities, transportation and mining operators, and building service suppliers [Swanson, 2003]. They can also serve in political processes by providing a systematic multi-criteria analysis approach [Rafi, 2001]. A relatively new concept is e-CMMS, which means that the application services of the CMMS are accessible via the Internet [Tsang, 2002].

In many companies the implementation of CMMSs is still in an early phase, mainly due to lack of interest and understanding, management commitment and personnel resistance, i.e. perceived threats to the position of maintenance staff and managers [Vonk and Smit, 1996; Jonsson, 1997; Llerena, 2000; Hanssson and Backlund, 2003; Ebdon, 2004]. Ulusoy et al. [1992] describe the implementation process at a foundry. Remarkably, people who helped develop the CMMS showed active resistance during the implementation. Ulusoy et al. suggested that, in hindsight, these people were not aware of the implications:

‘Previously, data was scarce and unreliable, preventing any kind of performance evaluation (...). But once implementation started they felt that the planning authority was put ahead of them and that they were controlled more closely than ever before. [Resistance could be overcome to a large extent], mainly by top management support and efforts to convince them that they themselves have a strong management tool to run their own divisions more effectively’.
Considerable development of CMMSs has been seen in the management of roads; first applications were installed in North America in the early 1980s and subsequently in Europe [Molenaar and Van Gurp, 1982; Ministry of Finance, 1987; Schijndel and Blok, 1993; CROW, 2001]. A few studies are now available, in which the effects of CMMS use have been analysed in detail, despite the difficulty of quantifying most benefits (e.g. reduced travel times, improved LCC, consistent and justifiable decision making). Arizona’s pavement management system was among the first (1980); it saved $100 million in the first four years alone [Golabi et al., 1982]. In Alberta, the pavement quality index increased, while the cost level remained equal; this has resulted in an increase in the average pavement life by 13.5% [Cowe Falls and Tyghe, 2004]. In Alberta, the data collected by the road management system was used to perform LCC studies with highly detailed data on (minor) maintenance.

Maintenance optimisation models can provide ‘intelligent search routines’ to find optimal maintenance strategies, considering the relationship between costs and benefits of maintenance, as well as the given constraints to the maintenance process [Dekker, 1996]. An easy-to-follow introduction to such models can be found in Campbell and Jardine [2001]. Because maintenance problems are extremely diverse and most of them are not repetitive, there is a wide variety of maintenance optimisation models available. Dekker [1996] notices that ‘analysing the data without knowing the underlying failure mechanisms can lead to entirely wrong results. Data has to be collected under strict rules, using a well-defined system-component structuring’. Most optimisation models used up to now have been difficult to understand and interpret. Dekker and Van Noortwijk [2001] reflect upon the situation as follows: ‘Mathematicians, who pay more attention to methodological elegance, develop maintenance optimisation theory, whereas consultants with little mathematical knowledge develop methods that are too pragmatic’.

Although state-of-the-art infrastructure management systems now use advanced techniques such as neural networks to predict future degradation and to select appropriate maintenance interventions [Cowe Falls and Tyghe, 2004], implemented CMMSs currently pay hardly any attention to optimising cost-effectiveness of maintenance planning in terms of system-wide life-cycle costs. They focus on single subsystems [Plasmeijer, 1999; Guigner and Madanat, 1999].

In the absence of CMMS (data), optimisation becomes complicated. Plasmeijer [1999] states: ‘one of the most remarkable facts within logistics is the lack of success of mathematical models in the field of maintenance planning’. He mentions several reasons why realistic maintenance models are hard to develop. Firstly, the lack of data on the degradation parameters of the components is a problem. Secondly, the dimension of maintenance problems, i.e. the fact that the components are prone to multiple damage features, while the maintenance manager has an extensive set of maintenance actions to choose from. Finally, the system itself is complex: there is an economic, structural and stochastic dependence between the components due to economies-of-scale for maintenance activities, the configuration and the interdependent degradation of the components. Dekker [1996] mentions expert knowledge as an alternative input, but states: ‘This, however, requires a reformulation of most maintenance optimisation models since it is very difficult to elicit probability distributions from people’. Moreover, well-known fallacies in the technique of Markov decision models, based on expert judgement, are the underlying assumptions that ‘the distribution of condition
states at time t+1 depends on the history of the facility only through the present state [and] that transition probabilities do not depend on age, (whereas) a large body of empirical work has shown that age is a significant determinant of a facility’s deterioration rate’ [Guignier and Madanat, 1999].

An overview of optimisation models for road maintenance can be found in Worm and Van Harten [1996], Plasmeijer [1999] and Guillaumot et al. [2003]. They describe approaches to include economies of scale and uncertainties. Plasmeijer [1999] uses regression analysis, expert judgement, the renewal-reward theorem, dynamic programming and marginal cost analysis to parts of the ‘maintenance problem’.

3.4.8 Usability of methods for instant LCM-support

Studying the basic ideas behind the discussed concepts and methods, it becomes clear that they all focus on parts of the ‘LCM problem’, i.e. *minimising the total costs of ownership for a maximised, or desirable (specified) level of performance (RAMS)*. However, they are all based on different starting points, resulting in entirely different concepts, each having strong and weak points. The concepts are summarised below and judged on their merits for use in a decision-support approach:

1. *Systems Engineering (SE)* is in fact a comprehensive methodology for setting up LCM-based design, operation and preservation processes. It defines step by step how to guarantee top-level performance objectives, such as RAMS and life-cycle costs (affordability), through, e.g. testing and commissioning procedures, integrated logistic support (e.g. spare parts management) and the set up of failure reporting systems. SE provides guidelines on topics to consider in a life-cycle approach, and can therefore serve as a framework for a decision-making set up. Because SE applies to the entire system management process, it is in the first instance the choice of the decision makers themselves whether or not to base the design process on SE; an analyst supporting the decision-making cannot make this choice.

2. *Total Productive Maintenance (TPM)* focuses entirely on bringing about a cultural change with respect to maintenance in order to maximise overall throughput and output of production systems. It uses a strict stepwise improvement programme, encompassing all maintenance and operations departments. Success in terms of system reliability and, subsequently, reduced costs of corrective maintenance can be tremendous [Tajiri and Gotoh, 1992], but it requires several years and continuous top management support. It is therefore not a concept for decision support in smaller, contemporary decision-making contexts, but more an overall vision of management; that management should be ‘ready’ to focus all effort on reliability. The success with ‘quality circles’, in which experts and managers from all organisational units are involved in order to identify root causes of problems, provides a useful direction for organising an LCM process.

3. *Reliability theory* provides usable ways to estimate reliability characteristics of systems with certain design properties (e.g. redundancy in functions); such models can be used within a decision-support approach, if detailed, well-validated data and time, required for the analysis, are available. This is surely a problem in ad-hoc, dynamic decision-making processes.
4. **Quality Function Deployment (QFD)** seems a good method for identifying the demands and desires of the customer at the end of the value chain. It is thus helpful in defining high-level performance objectives for the system, including maintenance. However, this implies that QFD will not provide support in design and preservation processes, where desired functionality is already specified.

5. **Reliability-Centred Maintenance (RCM)** and **Reliability-Based Inspection** assist in determining which maintenance actions and condition monitoring devices to deploy for providing certain reliability. This is important in LCM; however, they are weak in determining whether maintenance strategies and packages are cost-effective and whether a comprehensive set of strategies was studied.

6. **Economic analysis methods, such as LCC**, are known for being able to quickly deliver estimates on total costs of ownership, including performance losses, even with limited input data. It can use either empirical data or expert judgement (‘tacit’ state-of-the-art knowledge) in a transparent manner. Because LCC provides approved logic to select alternatives on the basis of their ‘value for money’, it seems a suitable vehicle for stimulating life-cycle-based thinking among decision-makers. Value Engineering (VE) can be used, if decision makers would like to optimise the functionality of new systems; LCC is also used in VE studies.

7. **Maintenance optimisation models** can help optimise strategies, but are only expected to be successful on well-demarcated ‘sub-problems’, such as the scheduling of maintenance tasks in regular rosters or optimisation of economies-of-scale in the development of maintenance concepts. In highly dynamic decision-making contexts, they are not likely to be successful, because they require detailed data, time and specialist support.

Looking at this overview, we can conclude that there is a large variety of methods and techniques developed in the maintenance management literature, which can probably be used for ‘empowering’ a life-cycle-based design and preservation process. Interestingly, the identified methods seem to complement each other with respect to their strengths and weaknesses. For example, it is acknowledged that the cultural change TPM can bring about will create an environment in which more quantitative tools, such as LCC, CMMS, reliability theory and maintenance optimisation, will function better [see Emblemstvag, 2003; Kirk and Dell’Isola, 1995; Woodhouse, 2001]. According to the last author, these concepts give TPM its necessary teeth, i.e. ‘the rule-sets and tools to link diagnosis of a problem to a best solution’. However, there is no principal reason why concepts such as QFD, LCC, RCM and VE, could not already be used in companies, where this cultural change has not yet been made; they can possibly help to introduce a life-cycle approach in design and preservation on a smaller scale.

Nevertheless, it is evident that a conclusive theory on how to deal with **life-cycle cost, performance and risk levels** in a single process, using the aforementioned methods, is missing in the maintenance literature. Dekker and Van Noortwijk [2001] argue that maintenance optimisation models are in fact the only scientifically ‘mature’ approach for developing optimal maintenance policies, but that optimisation is complicated due to the difficulty of modelling maintenance. They acknowledge that improvements can often also be realised through simpler methods and conclude that there is a need for simple, but scientific methods for ‘optimising’ maintenance in relation to total life-cycle costs. Many authors argue that
there is no standard approach for developing maintenance concepts, only general starting points and guidelines (see Sections 3.2 and 3.3) [see Waeyenbergh and Pintelon, 1992]. Woodhouse’s [2001] experience is that a mix of qualitative and quantitative methods is indispensable. He argues that, although it is always a trial-and-error exercise, selecting the methods can be best based on the ‘functional criticality’. Criteria for this include life-cycle costs, the risk of failure and the performance hindrance in the event of failure. Equipment at the top critical level, the ‘vital few’ (5-10% of the total assets), requires a quantitative performance analysis with LCC and cost/risk-optimisation tools. Equipment with a normal criticality (30-60% of the total) can suffice with structured rules, requiring at least RCM and RBI, while lower criticality items only need some ‘structured common sense filters’. Remarkably, systematic ex-post evaluations to demonstrate the effectiveness of the discussed methods in decision making, let alone comparisons of the methods, are seldom available; Smit [2004] notes that this is surely the case with respect to LCC applications.

Although a mix of methods may thus be more effective than a single method, LCC is selected as the primary basis for developing a decision-support approach. The usability of the other methods will be considered on a case-by-case basis. A foremost reason is the expected ability to introduce ‘life-cycle thinking’ among decision makers by revealing expected costs of ownership and operation. This should already have some impact in settings with a lack of data and unsure commitment. A second, practical reason is that too much research time and resources will be necessary to develop an approach that integrates a larger set of methods, considering the fact that a conclusive theory is missing. Elements of the other methods could be considered on a case-by-case basis. A final reason is the author’s expectation that attention at strategic management level is placed first on the ‘vital few’ of the asset population with high cost and performance impacts. A round of interviews with stakeholders in the Dutch rail infrastructure sector confirmed this expectation (see Appendix A). Section 3.5 discusses LCC in more detail, because of its important role in this study.

3.5 In-depth investigation of life-cycle costing theory

This section discusses the analysis steps in LCC and ways of dealing with uncertainties.

3.5.1 Conducting life-cycle cost analysis

LCC requires a process of conducting a life-cycle cost analysis (LCCA) for each of the decision alternatives, following a formal and consistent methodology, discussed by researchers such as Kirk and Dell’Isola [1995]. In the first step, economic criteria are identified for governing the decision to be supported; examples are the organisational planning horizon, the discount rate to be applied to future costs and revenues, and constraints resulting from the company’s technological and business policy.

In the second step, decision alternatives are developed and evaluated on their expected feasibility, effectiveness and market conformity. The generation of a broad range of possible decision alternatives can best be achieved through a creative brainstorm session (group members do not need to know each other, though it is important that they all come from similar levels in the organisation) [Kirk and Dell’Isola, 1995].
In the third step, LCCA is performed to assess life-cycle costs of each alternative. A cost-breakdown structure is made to identify possible cost components, including those related to system performance (e.g. RAMS). Only alternative-dependent costs need to be included in the LCCA; common costs, which are made indifferent to all selected alternatives, can be left out, as well as sunk costs of alternatives, which are fixed costs that are committed due to earlier decisions. Apart from the directly visible costs, more ‘hidden’ costs also need to be identified, including [Kirk and Dell’Isola, 1995]:

- collateral costs, i.e. costs that emerge in linked production systems and that change as a result of the decision taken;
- denial-of-use costs, i.e. ‘the extra costs or lost income during the life cycle because occupancy or production is delayed for some reason’; and,
- functional-use costs, i.e. that express the impact of an alternative on the production capacity (product units per time unit), e.g. due to limited production speeds.

The fourth and final LCC step concerns selecting the alternative with the best life-cycle performance. The theory is clear in that respect: when all costs and benefits are identified, the most cost-effective alternative should be chosen. However, an important part of this step concerns the mapping of uncertainties in the estimations and assessing the risks involved (see Section 3.5.2). The risk assessment should be adequate to make a sound economic ranking of the alternatives, provided that there is a basic level of reliability in the input data.

In LCC studies it is sometimes important to make a distinction between costs and expenses; cost is a measure of resource consumption, whereas expense is a measure of spending. Although these terms are usually intermingled, there is an important theoretical difference that needs to be considered in supporting certain investment decisions [Emblemsvag, 2003]. Spending is directly related to a capacity level provided for production, whereas resource consumption relates to the amount of capacity actually being used for the production. For example, consider a maintenance machine that is scheduled for an entire night to improve track geometry at a particular spot to a higher level. The contract requires the maintenance manager to pay for machine rental and labour use during a full night of eight hours; only some expenses for fuelling depend on the quantity of work. Hence, the expenses for this machine shift are, for example, € 4,000. The machine can deliver 200 metres per hour, and over an eight-hour shift it could therefore produce 1,600 metres at maximum (its capacity). However, on this particular night, the machine only completes 800 metres. Since fuel expenses were € 100, the expenses (the money spent) amounted to € 4,100, or € 5.125 per metre. However, the cost of the maintenance is only € 2,100 or € 2.625 per metre, while on this particular night there was a capacity surplus (unused capacity) worth 2,000 euro. This is an important difference. If such a situation occurs frequently, it should be analysed whether this is acceptable. Perhaps a maintenance machine could be rented, which would give lower productivity, but would, in the end, be cheaper to operate. In other words, the management has to match capacity to demand and not the other way around, as many companies seem to do [Emblemsvag, 2003].

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36 Emblemsvag notes that this situation is especially risky for organisations, such as government agencies, which have a significant free cash flow: they do not have to pay for debts and are tempted to invest too much, leading to
LCC concerns the consumption of resources, hence costs, in the long term. The timing of the costs is highly relevant; earning or saving a euro today is better than earning or saving one tomorrow, due to the opportunity cost of capital. A euro earned in 2002 can be invested and used to gain extra revenue, and has therefore higher value than a euro earned in 2020 (it can at least be put into a savings account). Future costs and revenues have to be expressed in their present value in the Base Year, in which the decision is made; a discount factor is therefore applied to all future costs and revenues.

In finding a reasonable discount rate, a distinction has to be made in for-profit companies and public organisations, and not-for-profit organisations. The former concerns private companies with access to the capital market for loans. Their investments are financed through these loans, resulting in debt, until revenues outweigh the costs of capital, and money of their own (equity). Without discussing the details, a Weighted Average Cost of Capital (WACC) can be calculated on the basis of market rates and the structure of debt and equity; this WACC can serve as the discount rate.

The cost of capital in the public sector is more complicated. These organisations often spend their money according to the budget they receive and the use of a discount rate therefore seems a bit artificial at first. However, Sugden and Williams [1978] argue that each individual and each organisation has a ‘marginal time preference rate (MTPR)’, which is equal to the market interest rate in the event that everybody can rent for the same interest rate. In reality this is not entirely the case. They therefore mention that the ‘social MTPR’ of society as a whole should be used for government-financed projects. Because this is not directly measurable, three proxy indicators are usually applied [Emblemsvag, 2003]:

- **long-term government bond rate.** This is the rate paid by government for acquiring capital; for non-governmental organisations, which cannot issue such bonds, this rate is close to the long-term market interest;
- **social opportunity cost rate.** This is the rate at which government projects generate a return that is at least equal to private-sector projects, which are ‘displaced’ by the fact that the government is acquiring the market funds;
- **modified WACC.** Although the public sector has no equity, taxes can be used instead; the inflation rate should be used to determine the cost of these taxes.

Although the issue of choosing a discount rate seems rather complicated, Emblemsvag [2003] and others simply suggest that the organisation decides itself on its role in society and selects a certain discount rate accordingly. In many countries, the government prescribes a certain discount rate to be applied in trade-offs by government agencies; this rate is then believed to represent macroeconomic effects in terms of opportunity costs. This seems a fair approach; although supply and demand are uncoupled for many government agencies, the government as a whole still has to buy money on the financial market under economic laws of supply and demand.

Inflation is another issue to be dealt with in LCC. Many economic situations are possible, leading to a different way of including or excluding inflation. However, if inflation

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structural surplus capacity. *Debt introduces correct spending discipline in that respect.* In LCC, interest costs should therefore always be included.
in the distinguished cost components is fairly low and not strongly deviating among decision alternatives, and if no long fixed-price contracts have to be considered, it suffices to use a so-called real interest rate [Emblemsvag, 2003]. This real interest is the nominal or market interest minus the consumer price index and allows all costs to be calculated with known unit-cost rates from the Base Year [Sugden and Williams, 1978]. Sometimes tax is also included in LCC, but it is difficult to model well over the years and often not meaningful; when tax is included, it is more to give an impression than to calculate real levels [Emblemsvag, 2003].

After discounting, all costs and benefits are comparable and can be used in the calculation of an overall outcome; several ‘presentation modes’ are available. Firstly, the Net Present Value (NPV) is simply the sum of all costs and benefits. The larger the NPV, the more attractive the investment is compared to alternative investments or maintenance strategies. However, if only costs are incurred, one speaks of a Total Present Value (TPV). Naturally, the larger the TPV, the more costs are involved and the less attractive the alternative. A second form of presentation is the Internal Rate of Return (IRR), which expresses the profitability of the particular alternative compared to a base case. The larger the IRR, the more attractive the investment is. A third way is the Annuity (ANN), which is the sum of interest and depreciation, to be paid every year for the particular alternative during the defined period (see Table 3.1 for the calculation of ANN); ANN is often used in mortgages, and anyone who has purchased a house will recognise it. ANN can also be determined for an infinite period of ownership, which is equal to the ANN for a single life cycle of the entire system. A final measure is Savings to Investment Ratio (SIR), which is the ratio of the present value of the annual cost savings by the initial cost [Kirk and Dell’Isola, 1995].

### Table 3.1: Some basic formulae for life-cycle cost analysis

<table>
<thead>
<tr>
<th>No.</th>
<th>Formula</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4</td>
<td>$TPV = \sum_{y=0}^{n} \frac{C_y}{(1+i)^y}$</td>
<td>The total present value $TPV$ is the sum of all discounted costs $C$ from Base Year ($y=0$) to the applied time horizon ($y=n$) analysed. The interest rate applied is $i$.</td>
</tr>
<tr>
<td>3.5</td>
<td>$a_{n,i} = \frac{1}{(1+i)^n}$</td>
<td>This is a helpful multiplication factor ($a$) is used to convert a cost of 1 euro occurring in the $n$ years analysed into its present value using an interest rate $i$. Used for (annually) constant running costs.</td>
</tr>
<tr>
<td>3.6</td>
<td>$ANN = \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \cdot TPV$</td>
<td>This formula is used to convert the total present value of the investment or maintenance strategy into the annual equivalent or annuity (ANN). This is the fee needed to finance the strategy during the years analysed.</td>
</tr>
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</table>

Detailed discussions on the selection and use of these LCC ‘performance measures’ are available in the engineering economics literatures; for example, Tang and Tang [2003] conclude that NPV is a better economic indicator for public works than IRR, which would be a better financial indicator for a private company; this is caused by the fact that NPV is not affected by variations in the financial arrangements, whereas IRR is. Similarly, there is much to do on the way depreciation is dealt with, although depreciation is mainly relevant to analyse the economic value of the capital base, at a given point in time, or to determine
residual values.\textsuperscript{37} Depreciation is a \textit{calculated} cost to pay back investments; there are several methods, e.g. linear versus accelerated depreciation, where value loss depends on age, and activity-based depreciation, where the value loss is determined by the ratio of actual asset use to estimated useful life. The above issues are less important if LCC is used to support management decisions rather than for detailed accounting purposes. In the first case, different strategies are compared and the focus is on relative differences in performance. Box 3.3 on the next page presents a simple LCC analysis example.

Many sources for input data are usually available for LCC studies [Blanchard and Fabrycky, 1998] but, first of all, a common ‘estimating framework’ is needed ‘to organise, keep track of, and allow easy access to these costs; all costs that make up the estimate should be consistent as to precision’ [Kirk and Dell’Isola, 1995]. A format is thus required that prescribes the necessary input data and guarantees that the same accounting basis is applied in the collected data. Data is not always processed in a uniform way. For example, infrastructure manager and supplier data differ because of mark-ups for overhead costs, risk, etc.

The required data is often not available directly, or not at all, due to uncertainties with respect to new technology and future operating conditions and, equally important, because of insufficient, volume-based accounting systems; ‘most organisations have too much data available but not the data we want’ [Emblemsvag, 2003]. It makes no sense to be more precise than the available data. The LCC exercise therefore usually starts with a ‘reconnaissance’, which means that the analyst(s) organises a number of meetings with stakeholders and independent persons in order to judge the effectiveness of more intense data collection efforts [Kirk and Dell’Isola, 1995]. Considering the availability of data and time constraints, the LCC study can be set up. Emblemsvag [2003] mentions four approaches:

1. \textit{Analogy models}. This is the simplest LCC method, but also the most rigid one; an analogy is identified between the target system or strategy and a similar, well-known system on the basis of a single cost driver.

2. \textit{Parametric models}. A more advanced way of cost estimating is to develop mathematical models that relate costs to the general characteristics of products and processes, such as manufacturing complexity. Emblemsvag warns that, although optimisation models can easily be used in this approach, they should be used with caution for systems in strong interaction with their economic, physical and political environment. Implemented solutions are probably not ‘optimal’ by the time that they are fully implemented.

3. \textit{Engineering cost models}. In these models, costs are established on the basis of firm engineering knowledge and estimates, using ‘cost-element relationships’. They can provide much better insight and are possibly the most appropriate to deliver early cost estimates, but they perform poorly in dealing with overhead costs.

4. \textit{LCC cost accounting models}. These models can only be used when considerable data on the ongoing production process is available. Instead of using estimation models on the basis of expertise and aggregate data, these accounting systems are based on collected data during the system life cycle, which is stored in the accounting system of the company. The systems are based on costing concepts such as Activity-Based Costing.

\textsuperscript{37} The \textit{economic value} expresses whether a ‘cost object’ produces sufficient profit to pay for its use of capital; if that is not the case, a company destroys its economic position [Emblemsvag, 2003].
Box 3.3: Example of a life-cycle costs calculation

Consider the following example: an investment is being made in a track component that will cost 2,000 euro and will be maintenance-free during the first year. In the following four years the maintenance will cost 100 euro; from the fifth year onwards the costs will increase annually by 20%. After 11 years the asset will be replaced and a new cycle starts, which is not considered here.

Using a 5% interest rate a depreciation plan can be made based on the annuity method. First the total present value is calculated using Formula 3.4 and eventually with the help of Formula 3.5. The annuity, which has to be paid over 11 years, is calculated with Formula 3.6. The annuity is the basis for the (linear) depreciation plan. The investment will lead to a debt of 2,000 euro, which will cost 100 euro interest at a rate of 5%. This means that in the first year 281 euro remain available for depreciation of the track asset etc.

<table>
<thead>
<tr>
<th>Year</th>
<th>Cost</th>
<th>Present value</th>
<th>Debt (Jan 1*)</th>
<th>Annuity</th>
<th>Interest</th>
<th>Depreciation (&quot;linear&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2,000</td>
<td>2,000</td>
<td>2,000</td>
<td>381</td>
<td>100</td>
<td>281</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>95</td>
<td>1,819</td>
<td>381</td>
<td>91</td>
<td>290</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>91</td>
<td>1,629</td>
<td>381</td>
<td>81</td>
<td>299</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>86</td>
<td>1,430</td>
<td>381</td>
<td>72</td>
<td>309</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>82</td>
<td>1,221</td>
<td>381</td>
<td>61</td>
<td>320</td>
</tr>
<tr>
<td>5</td>
<td>120</td>
<td>94</td>
<td>1,021</td>
<td>381</td>
<td>51</td>
<td>330</td>
</tr>
<tr>
<td>6</td>
<td>144</td>
<td>107</td>
<td>835</td>
<td>381</td>
<td>42</td>
<td>339</td>
</tr>
<tr>
<td>7</td>
<td>173</td>
<td>123</td>
<td>669</td>
<td>381</td>
<td>33</td>
<td>347</td>
</tr>
<tr>
<td>8</td>
<td>207</td>
<td>140</td>
<td>529</td>
<td>381</td>
<td>26</td>
<td>354</td>
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<tr>
<td>9</td>
<td>249</td>
<td>160</td>
<td>424</td>
<td>381</td>
<td>21</td>
<td>360</td>
</tr>
<tr>
<td>10</td>
<td>299</td>
<td>183</td>
<td>363</td>
<td>381</td>
<td>18</td>
<td>363</td>
</tr>
<tr>
<td>Totals</td>
<td>3,592</td>
<td>3,163</td>
<td>0 (yr 11)</td>
<td>4,189</td>
<td>597</td>
<td>3,592</td>
</tr>
</tbody>
</table>

![Depreciation plan based on annuity method](image)

After having prepared the basic LCC model, each decision alternative can be assessed; however, assessing the alternatives on the basis of the set of standard settings alone is not sufficient. Any LCC study should study the robustness of outcomes; available concepts and techniques are discussed in the next subsection.
3.5.2 Uncertainty analysis

The analysis should consider how uncertainties in data, the future environment, and the objectives of (other) parties can influence outcomes. A distinction can be made between alternative-independent (e.g. the general economic situation) and alternative-dependent uncertainties (e.g. risk of obsolescence for a certain technological solution). This subsection discusses a number of methods used in the LCC literature to deal with these uncertainties; it is not meant as an overview of the field of uncertainty analysis.

When conducting LCC, we are looking for methods that help 'to categorise the probability that, of two alternatives, the alternative with the lower computed life-cycle cost will in reality have the lower life-cycle cost' [Kirk and Dell'Isola, 1995]; we are less interested in whether the absolute values predicted in the analysis come true. As an illustration, the P-CR-002 Standard of the Norwegian offshore industry proposes Formulae 3.7 and 3.8 to compare alternatives [NORSOK, 1994]. Formula 3.7 combines the standard deviations of each cost element ($E$), when the cost elements are assumed independent, and uncertainty in the costs elements follows a Gaussian distribution. If Formula 3.8 is the case, then the finding that alternative A is better is considered robust.

$$\sigma_{TOTAL} = \sqrt{\sum_{E=1}^{n} \sigma_{E}^2}$$ (3.7)

$$LCC_A + \sigma_A < LCC_B - \sigma_B$$ (3.8)

where $E = $ a single cost element and $LCC = $ life-cycle cost

Uncertainty can never be (entirely) eliminated, as most systems are open systems in interaction with an environment; there will always be a lack of information or knowledge with respect to this interplay. In order to develop a picture of the risk taken with regard to each decision alternative, the risk in the outcomes of the cost elements has to be mapped. Risks can be defined as uncertain events, having negative consequences, either 'bad things happening' or missed opportunities, i.e. 'good things not happening'. The source of risk is uncertainty. Two theoretical schools have studied risk: probability theory and possibility theory. Both try to measure the risk, but the former does so in a quantitative, absolute way and the latter does so in a relative way with measures of degree. Possibility theory is intuitive, but less precise (fuzzy sets); though this does not have to be a disadvantage, because the hard data needed in probability theory is often absent [Emblemsvag, 2003].

A number of methods are used in the LCC literature, which have resulted from these two theoretical schools. Firstly, in some LCC studies, a so-called Expected Net Present Value (ENPV) is used (Formula 3.9). This is based on an 'event tree' of possible uncertain events if a particular decision alternative is chosen. The expected monetary value is based on the probability of each of these events occurring, and the costs that they imply. Several authors, e.g. Flanagan et al. [1989], advise against ENPV because it will never be the actual outcome and it does not consider the attitude of the decision maker. The model assumes that the user is 'risk-indifferent', but in many cases this is not true.
\[ \text{ENPV} = \sum_i (p_i \cdot \text{NPV}_i) \] (3.9)

where ENPV = the expected net present value, \( p \) = the probability, and NPV = the net present value of the consequences (costs and benefits) for each future event (i).

Kirk and Dell’Isola pose that the Confidence Index (CI) approach works well. The CI approach is based on the assumption that all cost data is normally distributed, as in Formula 3.7, and that the high and low 90% estimates for each cost corresponds to the true 90% points of the Gaussian distribution. They state that the CI approach can only be used if, among other things, the upper and lower estimates come from the same source as the best (mean) estimate, and if the estimates can be considered as knowledgeable judgements rather than guesses.

Sensitivity and scenario analysis are other, easy-to-comprehend methods for indicating levels of risk. Rather than producing a direct measure of the probability of a particular outcome, ‘a measure of the probability is approximated through judgement based on available cost information, as well as (1) the results of a sensitivity analysis and (2) a computed break-even point’ [Kirk and Dell’Isola, 1995]. It is therefore a more intuitive ‘what-if’ approach to analysing and understanding uncertainties. These methods are discussed in every LCC handbook. Sensitivity analysis determines how the value of a particular output, e.g. life-cycle costs, is affected by an input variable (e.g. the interest rate can impact many cost elements). If the values fluctuate strongly, then the output is sensitive to this parameter. Having performed the sensitivity analysis, the results can be presented in several graphical ways, e.g. using spider diagrams. Scenario analysis is a simple method that can easily complement the sensitivity analysis. The analyst constructs scenarios concerning the possible future states of the system and its environment, in conjunction with experts and decision makers. These future states are systematically translated into specific values of the input parameters [Koevoets, 2000]. If the uncertainty is limited to a few factors, this approach provides useful information.

Sensitivity analysis is helpful, but in the case of complex systems it can be too limited because it is a univariate method; only one variable is tested in each model run, and possible interactions between the factors may therefore not be revealed. If more dominant cost drivers are found, a multivariate method is generally suggested [see Flanagan and Norman, 1983]. The statistical method of Monte Carlo simulation is therefore gaining popularity, also thanks to modern computer power.

Monte Carlo simulation can quickly simulate the entire system without flaws and can deal with all kinds of input, irrespective of their format: discrete, continuous, stochastic, fuzzy etc. In Monte Carlo simulation, the ‘response’ in a single model run is a simple function of the stochastic input variables. Many runs are made using a random generator, each delivering an independent observation. Together they constitute a probability distribution of the expected, overall life-cycle cost. ‘It is like conducting a political survey; although you interview only 1,500 individuals, you have a pretty good idea about the overall opinion of the population’ [Emblemvang, 2003]. The main principle behind Monte Carlo simulation is the Central Limit Theorem, which states that a Gaussian probability distribution will result from a large number of (independent) observations. Changes in the LCC model structure are not required for including Monte Carlo simulation in the LCC model (see Figure 3.17). Risks are
identified for each cost item that can influence the value of the base items, and a statistical distribution is developed for the possible value of the item (e.g. Triangular distributions are often used). After the runs, the probabilities of certain life-cycle cost outcomes can be deducted for defined levels of confidence.

![Diagram of Monte Carlo simulation process for LCC](image)

**Figure 3.17: The Monte Carlo simulation process for LCC [after Flanagan et al., 1989]**

Once all insight is provided on the likely outcomes in terms of life-cycle costs, the final choice is up to the decision maker. The choice might still not be clear-cut, where the decision maker faces different risks for different courses of action. Also in this respect, criteria have been developed in the decision analysis literature to support decision makers.\(^{38}\) An introduction into the field of decision analysis can be found in Emblemsvag and Fabrycky [1998]. State-of-the-art research on uncertainty in LCC applications (to infrastructure management) can be found in Kishk and Al-Hajj [2003] and Salem et al. [2003].

Finally, note that considerable progress has been made over recent years in scientific research of investment analysis, which has a consequence for cost-benefit analysis methods

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\(^{38}\) An example is the 'Minimax Regret Criterion', which selects the alternative that minimises the maximum 'regret' of the decision maker. Regret is calculated for each alternative; it is defined as the missed profit compared to the maximal positive outcome, if another alternative is selected, or the extra loss compared to the minimal negative outcome, if another alternative is selected.
that are based on net present value calculations. New insights into the behaviour of companies, concerning investments, have led to the ‘real options theory’ [Dixit and Pindyck, 1994; De Neufville, 2001]. Cost-benefit analysis, using discounting, ignores the fact that there may be a ‘moving baseline’ in the overall industry and presumes that there is a ‘discrete choice’, at a certain point in time, between different alternatives. All costs and revenues of the alternatives should be incurred, once the choice is made (resulting in a net present value). In uncertain environments, this is often not a realistic representation of reality. As an illustration, it is possible to first invest in an innovative research project using limited funds in order to obtain more reliable information on whether the project might deliver the full, expected benefits. After a while the project can be fully started or stopped, if convincing information could not be obtained. It is thus possible to calculate an ‘option value’ for the project, similar to financial options. Dixit and Pindyck [1994] can thus explain ‘hurdle rates’ of companies in investments, which prove to be 3–4 times the cost of capital.

3.6 Conclusion: LCC as a vehicle for introducing a life-cycle approach

Chapter 2 ended with the conclusion that relatively much (fragmented) R&D have started in the rail infrastructure sector that try to contribute to a systematic performance-based decision-making process, in which cost and performance levels can be well defined, guaranteed and improved. This chapter showed that this search is part of a broader research challenge, which is more and more referred to as ‘asset life-cycle management’ (LCM). Although many different definitions and notions on LCM can be found in the literature, it can be concluded that decision making in an LCM or ‘life-cycle’ approach should:

- consider costs and quality effects of maintenance and other ‘downstream’ expenses (e.g. energy consumption of buildings) from the first design phase onwards;
- specify functional requirements (RAMSHE and affordability) for the production system in order to develop technical specifications;
- aim to optimise subsystem design and maintenance strategies on the basis of minimal life-cycle costs; and
- make use of empirical data, obtained from experiences with previous systems, in the forecasting of the downstream costs (including costs of non-performance).

A life-cycle approach to design and maintenance should thus be able to improve decision-making in a capital-intensive industry such as the railway sector in the following ways.

- **Improving the cost-effectiveness of designs and maintenance strategies through:**
  A. Reducing sub-optimisation at the level of single management processes such as construction, maintenance, renewal, and transport operations.
  B. Reducing sub-optimisation at the level of single technical subsystems such as track, power supply and signalling by analysing cross-impacts.

- **Improving the quality of the decision-making process through:**
  C. Avoiding implicit design and maintenance choices through a systematic, transparent selection process of alternatives.
  D. Avoiding chaotic or unclear decision-making processes by creating a systematic decision-making process.
The literature review also made clear that a life-cycle management approach is far from common practice. A reason is the complexity of today’s production systems. This demands far-reaching specialisation in design, maintenance and operation, which makes it difficult to develop comprehensive operation and maintenance models, and leads to fragmentation in perceptions and interests. Although a range of methods and techniques has become available in the last decades that are useful for an LCM approach (see Section 3.4.8), LCM is not yet a concept with a consistent, clear-cut set of working methods. Apart from the lacking attention and support for LCM, a probable reason is the variety in production systems, which may require sector-specific LCM approaches. Moreover, there is no conclusive theory on how best to introduce LCM or ‘life-cycle thinking’ on the ‘shop floor’ of the production system.

Of the identified methods, life-cycle costing (LCC) was expected to be particularly suited to introducing life-cycle thinking in dynamic decision-making processes, where a lack of data and commitment for LCM is expected. Although the general hurdles for ‘LCM’ should also hinder (to an unknown extent) an LCC-based approach, it was expected that LCC should have a good chance of success in enabling ‘life-cycle thinking’ in daily decision-making. The development of the LCC-based supporting approach will be further pursued in the following chapter.

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39 As mentioned, the Systems Engineering process may well serve as an encompassing methodology for elaborating industry-specific ‘LCM models’. As argued in Chapter 1, it is not the author’s intention to develop an encompassing ‘LCM model’ for the railway sector, but to explore how life-cycle thinking can immediately be stimulated in actual decision-making processes.

40 Goel [2004] has similar findings regarding the (process) industry.

41 Also the LCC literature recognises this difficulty. For example, Kirk and Dell’Isola [1995] state that ‘the (LCC) study effort may be rendered ineffective by the imposition of a criterion other than long-term economy.’
4. A Decision-Support Approach

This chapter develops an approach to support the introduction of a life-cycle approach to designing and preserving rail infrastructure in contemporary decision-making in the railway sector. Section 1 reflects on the reality of everyday life in such (public) organisations, using some insights from the field of policy science. Section 2 proposes using a decision support system (DSS) for estimating railway life-cycle costs and performance as the centrepiece of an approach to supporting rail infrastructure managers (IMs). Section 3 details the structure that such a DSS would have. Section 4 concludes with a description of the process that was set up for testing the effectiveness of the decision-support approach.

4.1 Introduction: decision support in multi-actor environments

In Chapter 3 it was argued that IMs often lack an inherent drive to develop a life-cycle management (LCM) approach to the system under their responsibility. This section uses insights from policy science to find a way to encourage LCM within such an IM. The policy science literature deals with strategic and tactical decision-making in public and semi-public organisations; two different schools have been studied. These are briefly introduced in two subsequent subsections. A final subsection reflects on recent ideas in the field and on the consequences for the viewpoint that is adopted in this publication. The set-up and content of the next two subsections were inspired by Edelenbos et al. [2003], who provide an up-to-date description of the field of public management.

4.1.1 The analytical approach to policy making

The end of World War II marked the beginning of an analytical view on policy making. The success of operations research (OR) techniques, such as optimisation, in military planning led to these techniques also being embraced for civil policy making; a discipline emerged which was first called ‘system analysis’ and later ‘policy analysis’ [Quade, 1989; Van de Riet, 2003]. Quantitative techniques from OR and economics dominated this discipline during the first decades after the war, the objective of which was to provide ‘rational’ advice to administrations with respect to public policy. Cost-benefit analysis techniques were already in use a few years after the war and were later extended to include social and environmental effects. Since it became clear that cultural, organisational and political factors were also
important aspects of policy making, the ‘tool box’ was gradually extended with approaches to deal with these factors.

The analytic approach was originally based on the perception that ‘decision-making should be rational and be supported by rational analysis’ [Edelenbos et al., 2003]. Rationality originally meant that an actor acts on the basis of value maximisation; the choices he/she makes should be the best means to achieve the stated objective [Majone, 1989]. Later, findings from Simon [1969] were also accepted. He showed that individuals in real life do not choose on the basis of value maximisation, but on the basis of ‘satisficing’. As a result of lacking information and capacity, people are bound by their rationality; and therefore choose the first solution that is good enough for them. Nevertheless, ‘rationality’ should be reflected in the procedures followed to come to the final choice and in the content, namely the use of an explicit policy theory with goals and constraints that reflect its values well in terms of efficiency and effectiveness. Decision-making should take place in a number of stages that reflect different human intellectual exercises, i.e. intelligence (the problem is analysed and the decision aims and evaluation criteria are formally denoted), design (possible decision options are designed and combined into strategies), and choice (strategies are assessed on their consequences and the best strategy is selected) [Simon, 1969; Hoogerwerf, 1985]. Bahl and Hunt summarised this well (see Figure 4.1).

![Decision Model Diagram]

Figure 4.1: A general decision model [Bahl and Hunt, 1984]

This approach presumes that it is possible to collect objective knowledge on reality as it is and that governments operate as single, unitary bodies; a choice can be made at a top level and is implemented accordingly. Failing policy is due to shortcomings in the ‘policy theory’ underlying the process, and scientific knowledge should eliminate these shortcomings in order to make decision makers behave more rationally. With respect to LCM, it means that the organisation should be assisted in developing a scientific policy theory on the cost-effectiveness of different design and maintenance strategies, and that decision makers will act accordingly, e.g. thanks to the implementation of a performance payment regime that eliminates undesirable behaviour or computer systems which deliver missing information.

Over time, insight gained into the (dynamic) nature of decision-making led to changes in the traditional view. It was, more or less, acknowledged that policy-making often concerns
ill-structured, 'wicked' problems, in which many stakeholders, e.g. individuals, organisational units and organisations, are involved, each having different, often conflicting perceptions, interests, and resources [see Linstone, 1999, p.52]. As a result, new approaches to policy analysis emerged that focus more on the decision-making context. In these approaches, providing timely policy information is no longer considered a sufficient condition for successful policies; active participation by stakeholders in the analysis and quality of argumentations is also important [Mayer et al., 2004]. To some extent, policy analysts become 'process architects and facilitators' who try to develop commitment to the analysis and its outcomes. Examples of often-used methods are:

- workshops, designed to involve key stakeholders in the analysis process;
- (quick-scan) stakeholder analysis studies, in which the interests of the various stakeholders in the particular problem are explored and confronted, in order to find opportunities and obstacles for the policy process [see Bots et al., 2000];
- gamings, in which policies are tested in a computer-based support environment and gameplay (see Section 1.3).

4.1.2 The process management approach to policy making

The process management approach is rooted in criticism on the view of governments as unitary bodies that develop phased 'rational' policies (the so-called stages model). Lindblom [1959] found that policy-making is more a process of 'incremental change'. Short-term and long-term interests of individuals and groups intertwine in these processes, and decision makers usually rely on proven courses of action because they have limited information on the impacts of decisions. This leads to a process of give and take, in which many groups in the society or organisation participate in order to influence policies. These groups develop a 'negotiated environment' in order to regularise the reactions of other groups, using budgetary splits, accepted areas of responsibility and 'established practices', so-called standard operating procedures (SOPs) [Allison, 1971]. As a result, organisations and individual decision makers have fuzzy, implicit objectives and participate in negotiating games, in which they consider their options downward (how to preserve my leeway until time clarifies uncertainties?), sideways (how to get others committed to my coalition?), and upward (how to give the boss confidence in doing what must be done?) [Allison, 1971].

This criticism led to the development of two types of models that replaced the rational 'stages model'. Firstly, there are 'stream-based models', which consider policies to result from the interaction between separate streams of problems, solutions, choice moments and participants, e.g. problem owners and providers of technology [Cohen et al., 1972]. Decisions can be made at moments when the streams come together; these moments are known as 'policy windows' [Kingdon, 1984]. Secondly, there are 'round-based models', which presume that a policy is the effect of a series of intermediate decisions made by several actors. Clear rounds can be identified that deliver key decisions, which then form starting points for further decision rounds [Teisman, 1992]. A solution or problem is only relevant when it is represented by one of the parties involved, and policy is only considered successful when the results satisfy the participating actors. An interesting case study on the strategic behaviour of actors in the field of infrastructure maintenance can be found in De Jong and Aijō [2001] or, in a Dutch version, in Ten Heuvelhof et al. [2003].
In this view on policy making, ‘interaction is considered important because policy development is seen as a political bid for power, dominated by strategic considerations’ [Edelenbos et al., 2003]. It has important consequences for recommendations to decision makers on the design and management of policy processes; success depends on the quality of this interaction and the interaction strategies chosen. In the stream-based paradigm, a failing policy is caused by a lack of innovative capacities to couple the streams of solutions, problems and actors. In the round-based paradigm, flaws in the interaction strategies of the actors cause failing policies, e.g. design or maintenance strategies that are not considered satisfactory by the stakeholders. The simple, rigid implementation of a performance regime, for example, is therefore not a sufficient solution to stimulate LCM. As long as performance cannot be defined unambiguously, it will create ‘perverse incentives’ among the stakeholders, both professionals and managers, to veil actual performance [De Bruijn, 2003]. It will result in strategic behaviour to show a favourable picture or to improve results in an unintended way, e.g. by focusing on easy-to-realise ‘cash cows’ instead of uncertain, innovative products or projects.

The ‘process management’ approach has produced a range of principles and strategies to improve progress in the policy processes and strategies of individual actors, in order to achieve support from other actors. These are discussed in De Bruijn et al. [2000]. Conflicting interests are not considered problematic. Instead of a reductionist approach, i.e. breaking down such problems into smaller problems which are treated one by one, process management rather interweaves and couples different issues to each other by ‘broadening the problem’; a stakeholder can thus lose some ground in one issue, but still be interested in cooperating because it wins more with respect for another issue (e.g. package deals).

The ‘process management’ approach has produced a set of strategies and design rules for the ‘architecture’ and management of policy processes. Examples are [De Bruijn and Ten Heuvelhof, 2002]:

- giving stakeholders an opportunity to advance their own interests;
- creating repetitive dependencies and a sense of urgency (because actors become more dependent on each other, which enhances cooperative behaviour);
- making a loose coupling between research studies and decision-making in order not to have stakeholders refrain from participation (results of joint studies will not directly be authoritative for the decision to be taken);
- giving stakeholders an exit option or an option to postpone commitment;
- avoiding opportunism, because it can work as a boomerang; and,
- inviting important actors to participate, because they can otherwise slow down the implementation of decisions (objection power).\(^{42}\)

The advantages of process management are evident, but this approach also experienced some shortcomings. Firstly, the resulting ‘negotiated knowledge’ considers only the interests of participating actors and its legitimacy can therefore become questionable.

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\(^{42}\) They mention, as an example, the ‘centralisation paradox’ for organisations with many professional workers. If the management opts for more centralised steering, without the commitment of lower echelons in the organisation, it may result in a huge information need, which makes top managers again dependent on their professionals.
[Edelenbos et al., 2003]. Secondly, one runs the risk of ‘becoming imprisoned by procedural questions’ and ‘an almost infinite process of goal-seeking policy processes’ [Edelenbos et al., 2003]; this is due to the focus on the process side of policy processes and a consequent lack of ‘substantive’ policy baggage.

As Edelenbos et al. [2003] argue, ‘representatives of the process management approach have started to realise that the substantive aspects of policy should not be denied and that information dissemination and research can lead to shared knowledge’. They mention that ‘the first attempts to design methods for “joint fact finding” have arisen’. This leads to the remarkable finding that, while policy analysts are making efforts to better consider ‘process aspects’ in their work, policy scientists who follow the ‘process management approach’ are looking at ways to incorporate ‘substantive aspects’ into their policy process designs.

4.1.3 Conclusion: participative policy analysis for successful decision support

An observation that can be directly made is that the methods mentioned in Chapter 3, including LCC, implicitly assume a single rational stakeholder to manage the entire production system; they therefore do not seriously consider the ‘process aspects’ that might be involved when introducing LCM. As Geraerts [1992] argues, ‘the view of industrial engineering in an organisation essentially comes down to viewing an organisation as an interrelated set of processes, the output of which can, and must, be influenced by planning and control’. This seems, at least for the rail sector, to be far from reality and insights from the field of public management are thus more than useful.

The author adopts the view of contemporary policy analysis (PA), which is that knowledge must not only be scientifically sound, but also relevant to the policy debate [Van de Riet, 2003]. This leads to a number of additional requirements that need to be taken into account as much as possible (see Table 4.1). This viewpoint leads us to conclude that a supporting approach can only work out successfully if it improves both the quality of the process and the resulting decisions. If requirements M0, M1 or M2 are not met, one or more stakeholders will consider the outcomes as irrelevant or invalid or will receive them with mixed feelings; this does not mean that the support provided is immediately useless – it can still produce ‘useful knowledge’, but it will have less impact on the policy process [Van de Riet, 2003].

<table>
<thead>
<tr>
<th>Single-actor complexity</th>
<th>Multi-actor complexity (extra demands)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>S0: Scientifically sound analysis</strong></td>
<td><strong>M0: Trustworthy analysis</strong></td>
</tr>
<tr>
<td>- Valid data, models, techniques</td>
<td>- Involving analysts who are trusted</td>
</tr>
<tr>
<td>- Verifiability/accessibility of analysis</td>
<td>- Using quality guidance groups</td>
</tr>
<tr>
<td>- Making analysis accessible for stakeholders</td>
<td></td>
</tr>
<tr>
<td><strong>S1: Structured search for policy options</strong></td>
<td><strong>M1: Bridging interests</strong></td>
</tr>
<tr>
<td>- Structuring objectives</td>
<td>- Multi-actor point of view</td>
</tr>
<tr>
<td>- Systematic, creative search</td>
<td>- Maximising benefits, minimising losses, identifying irreconcilable differences</td>
</tr>
<tr>
<td><strong>S2: Broad research focus</strong></td>
<td><strong>M2: Multi-perspective research focus</strong></td>
</tr>
<tr>
<td>- All relevant parameters/effects included</td>
<td>- Multiple problem definitions (multiplicity)</td>
</tr>
<tr>
<td>- Dealing explicitly with uncertainties</td>
<td>- Insight into distribution of gains and losses</td>
</tr>
</tbody>
</table>
In doing justice to these requirements, it was decided to develop decision support from a modern policy analysis viewpoint. This means that the analyst(s) should take responsibility in steering the ‘fate’ of the analysis through building commitment among stakeholders. The findings of policy scientists on the importance of analytical and process aspects should therefore be reflected in a set of ‘success criteria’, composed for the design and evaluation of our approach. Although a standardised evaluation framework is unavailable in the literature [Twaalfhoven, 1999], the list of success indicators put forward by Thissen and Twaalfhoven [2000] was considered adequate for composing the evaluation framework (see Table 4.2).

Table 4.2: Criteria for evaluating the effectiveness of LCC

<table>
<thead>
<tr>
<th>Criteria for success from PA viewpoint</th>
<th>Indicators taken from Thissen &amp; Twaalfhoven [2000]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Contents: cost-effectiveness of designs and maintenance strategies</strong></td>
<td></td>
</tr>
</tbody>
</table>
| Increased ‘richness’ of information used for design and maintenance choices | 1. Insight into situation and alternatives  
2. Identification of knowledge gaps  
3. Increased number of alternatives considered  
4. Manageability of the valuation of alternatives |
| Improved (expected) cost/performance ratio of design and maintenance choices | 5. Selection of more cost-effective alternatives  
6. Increased robustness (thanks to a broad analysis of alternatives and future conditions) |
| **Process: quality of interactions and cooperation** | |
| Improved ‘legitimacy’ of design and maintenance choices | 7. Reformulation of policy targets (‘reframing’)  
8. Increased actors’ commitment to decisions taken  
9. Change in actors’ positions (i.e. willingness to seriously consider new alternatives)  
10. Improved relationships/understanding |
| Improved ‘lead time’ of design and maintenance choices | 11. Reduction of time needed for decision-making  
12. Increased ‘sense of urgency’ among actors (i.e. they see a need to accelerate decision-making) |

This framework should provide a ‘rich picture’ on the success of this supporting approach in terms of process and outcomes. Moreover, the list of Thissen and Twaalfhoven [2000] was useful for compiling a list of input conditions that is expected to influence the effectiveness of the provided support; again, there is a distinction between content and process influencing factors (see Table 4.3).

Table 4.3: Conditions within the organisation that could influence the effectiveness of LCC

<table>
<thead>
<tr>
<th>External factor</th>
<th>Desired condition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Content controlling input</strong></td>
<td></td>
</tr>
</tbody>
</table>
| Available time for analysis | Sufficient time available  
In-time availability of required information |
| Available expertise and data | Sufficient empirical data from various sources  
Sufficient participation by qualified technical staff  
Equal/fair participation of all parties involved |
| **Process controlling input** | |
| Degree of independence and organisational embeddedness | Right moment to start the analysis  
Sufficiently intertwined with decision procedures  
Sufficient management support  
Absence of unspoken reasons behind the analysis |
4.2 A DSS as the starting point for analytic support

With respect to the support of LCM, the issue now arises of how to generate and provide information about such items as life-cycle costs and infrastructure reliability in a multi-stakeholder setting. Relevant questions are: How to generate required trustworthy information in dynamic, sometimes turbulent decision-making processes? How to disseminate (intermediate) outputs so that they materialise in the decisions taken? How to consider the implications that LCM may have for important stakeholders? This section proposes a practical way to support the introduction of lifecycle-based railway design and preservation; Chapter 3 already argued that, of the identified analytical methods, LCC would probably be the most helpful.

Because of the dynamic character of decision-making, it was deemed important to develop a flexible process for collecting and processing of LCC data. An interesting concept found in the literature concerns the decision support system (DSS), which emerged in the 1970s, along with the growing power of computers. A DSS can be defined as 'a computer-based information system consisting of hardware, software and the human element designed to assist any decision maker at any level, but with an emphasis on semi-structured and unstructured tasks' [Bidgoli, 1989].

DSS theory revolves by definition around the issue of providing flexibility in analytic support, although it is intended for repetitive use. The DSS concept aims to provide human decision makers with a variety of models to estimate impacts of different courses of action [see Carter et al., 1992], with the ambition to support the entire 'event structure of human choice' – from problem investigation to choice of a preferable alternative [Bahl and Hunt, 1984 – see Figure 4.1]. A DSS should generate new knowledge or explicate existing knowledge related to these steps. The DSS concept is therefore different from other applications, such as expert systems (in their strictest form) and management information systems (MISs), which focus on automating human tasks or collecting empirical data on work processes. In order to provide flexibility in terms of the sequence of decision steps and the particular information needs, a DSS should, ideally, be built of three separable elements [Bidgoli, 1989; Finlay, 1994], i.e. a:

- **database**: the DSS contains a database consisting of (aggregated) data on important work processes (e.g. productivity rates) or external factors (e.g. interest rates). Apart from empirical, raw data, expert knowledge can be an important source for input data;
- **model-base**: the DSS contains models for using data to provide estimates on performance and costs for alternative courses of action by the decision maker (e.g. a Net Present Value calculation model for simulating the effects of interest over time);
- **user interface**: the DSS usually contains screens to facilitate the use of the DSS by decision maker(s) and to present results in an understandable, auditable way (e.g. graphics screens).

Several authors listed possible functions of a DSS in single- and multi-stakeholder settings [Forgionne and Kohli, 1998; Van der Heijden, 1986], and their usability in railway engineering and maintenance seems evident.
1. *Diagnosing problems and opportunities*. Impacts of (restrictive) maintenance, operating and financial conditions can be analysed. An example is an analysis of the consequences of introducing a new, or already implemented, performance payment regime for infrastructure maintenance.

2. *Formulating and eliminating alternative courses of action*. The influence margins of the design and maintenance processes on the problem can be explored; a quick-scan of alternatives can be used to pre-select promising alternatives etc.

3. *Evaluating alternative courses of action*. The DSS can be used for identifying robust and cost-effective design and maintenance alternatives by analysing life-cycle costs.

4. *Monitoring and early warning*. Once LCC-based designs and maintenance strategies have been implemented, it is possible to evaluate (at a later stage) whether the assumptions have come true and whether the implemented strategies are still preferred. As such, the DSS can function in a process of continuous improvement.

Although DSS was initially meant as a concept for the entire process of human decision-making, including the provision of *process support*, mathematical modelling was the core of DSS theory until the 1990s [Finlay, 1994]. Problems that occurred as a result are [Klein, 1990]:
- a tendency to overemphasise decision-making;
- an unintended transfer of power and other unanticipated effects (e.g. obscuring of responsibilities); and,
- a false belief in objectivity.

Many problems occurred because users applied DSSs to problems for which they were not originally developed. Bui [1997] argues that DSS deployment has remained limited due to unawareness by potential users, problems in matching DSSs to specific problem situations and the high costs of data integration. Another problem found in DSS literature is that certain people simply might not be willing to make things explicit as this might initiate a discussion on real motivations, because the decision has in fact already been made, or because their goal is 'to have the alternative they have chosen adopted' [Klein, 1990]. He sees this as a problem for the decision maker and not for the analyst, which is, however, not the starting point of this publication (see Section 4.1.3).

Over the past few decades, the attention for the process aspects seems to be increasing in DSS theory. Finlay [1994] mentions that mathematical modelling is no longer a 'doctrine' in DSS development. Klein [1990] confirmed this; suggesting that the natural evolution of many DSSs is that the user also gets involved in the design (user-designer principle). The key explanation is: 'The system given to the user does not initially solve the problem, but creates an environment within which he or she will be able to solve the problem better than before'. Klein argues for an adaptive process of learning and evaluation where consultants play the role of chauffeur until the DSS constitutes 'an environment attractive enough for the end-users (...) to have it [the DSS] as a permanent assistant in their office'. Van der Heijden [1986] mentions that an analyst can certainly be 'part' of the DSS when the planning process is a group activity, because direct interactiveness is less important than responsiveness. He notices that 'chauffeured system use' can even be more efficient and effective, because it requires less effort by the decision makers and provides more opportunities to make them understand the meanings of the outcomes.
Although DSS theory is mainly based on the ‘rational stakeholder’ viewpoint, the idea of a DSS as a flexible ‘information-generating instrument’ still seems rather fitting for the dynamic nature of decision-making processes in multi-stakeholder settings. The aforementioned drawbacks were not considered principle objections to the use of a DSS as a starting point, as long as the DSS could serve as a tool to ‘speed up the learning process of the user’ [Klein, 1990] within a participatory analysis process with the stakeholders. However, an important issue was the fact that DSSs are in general meant for a more repetitive use while, in this research, the DSS would be used for a first time in unique, dynamic decision-making contexts. It was anticipated that the following approach could overcome this issue.

- A generic DSS structure is developed in advance, consisting of a number of standard calculation steps, to be followed in some detail; this allows the development of a preliminary model-base, on paper and in a computerised prototype, which should be ‘extendable’ depending on actual needs. The role of the DSS would primarily be in evaluating different decision alternatives on their life-cycle costs.
- The calculation steps would not model subtle, difficult-to-trace interactions, influencing asset degradation, avoiding the DSS becoming an intelligent ‘predicting tool’ itself. This use of a DSS as sophisticated ‘calculator’ would keep three ways of input generation open: (1) aggregated empirical data, (2) expert judgement, and (3) degradation models, if available. Appendix C contains a list of input data.
- The author functions as (one of the) DSS chauffeur(s), which would create more flexibility to adapt and ‘fine-tune’ the DSS to the requirements of the actual managerial context. Modification of the models could be an inherent part of a participatory analysis process that is meant to involve stakeholders.

It was decided to develop a computerised prototype, called LifeCycleCostPlan or simply LCCP, in a practical, engineering environment. This was achieved in cooperation with the maintenance contractor Strukton Railinfra; a pilot study with the DSS was subsequently realised within the context of a study for the Autonomous Community of Madrid (see Appendix D).

43 Handbooks on ways to elicit expert judgements for DSSs are available [Meyer and Booker, 1991].
44 The roles of the DSS chauffeur, LCC expert, and process facilitator can be united in a single person, or may be distributed between a couple of people who work together on a daily basis.

4.3 A decision support system for life-cycle cost analysis

A first activity was the development of a conceptual model on global mechanisms causing infrastructure degradation, M&R and LCC; the model was built in steps, in close collaboration with railway engineers, and was expected to help position the DSS in the estimation process. An overview of the model is introduced in the following subsection, followed by the DSS structure. N.B.: only the ‘top layer’ of the model is included here as it is sufficient for introducing the DSS structure; a further elaboration of this top layer is possible in more detailed sub-models (see Zoeteman [1998; 2000a]).
4.3.1 Conceptual model and structure of the DSS

The conceptual model is set up from the perspective of a separated IM. Those factors that the IM can directly influence are called steering variables. Others, controlled by other actors or entirely exogenous (e.g. subsoil quality), are called external variables. Steering and external variables together influence the infrastructure quality, which leads to an M&R process (visualised through internal variables). In the end, this process influences overall cost and performance levels, i.e. the effect variables (see Figure 4.2 on the next page).

The separated IM has two key ‘steering instruments’, i.e. its design and its maintenance policy. The design policy is reflected in the features of the design (e.g. readjustability and replaceability of components, investment in substructure quality, quality of materials, facilities for maintenance and incident handling such as crossover switches and sprinkler systems in tunnels) and the chosen construction method (e.g. prefab or in-situ). The design will directly influence the life-cycle costs via the costs of construction, and indirectly via the initial and inherent design quality. Construction costs are also influenced by external factors, such as site accessibility, safety legislation, and budget schemes, and unit rates for materials, machines and personnel.

Once its operational phase commences, the system is subjected to loads from traffic and physical conditions (e.g. settlement and rust); the deterioration of its initial quality will, over time, trigger events that impact its performance and operational costs. Maintenance standards, which are part of the overall maintenance policy (or simply legally required), define when inspection and maintenance are necessary. They intend to guarantee safety, riding comfort and noise levels, which are effect variables that do not have our primary attention, as previously mentioned. Any alternative to be considered should first meet defined requirements, related to those variables.

Within these constraints, it is the IM’s task to develop a maintenance policy that leads to a cost-effective management of the rail infrastructure in the long term; depending on the choices made, it results in certain needs for preventive M&R in order to avoid potential failures or undesirable degradation patterns in a timely manner. There may always be a number of inherent, unavoidable failures due to the quality of the initial design. Part of the maintenance policy is therefore to establish a failure-response organisation with certain costs and a certain performance in terms of repair times. All kinds of choices are involved in the maintenance policy, such as the work methods and equipment used, the repair concept (e.g. a full repair or a quicker, temporary repair method), the spare parts in stock, the clustering of maintenance, the speed restrictions applied, and the priorities given to different railway lines.

In the actual performance of M&R, a distinction needs to be made between the planned M&R volume, resulting from the chosen maintenance policy, and the volume actually realised in a given period. The realisation of M&R plans can be hindered by the availability of funds, track possessions, machinery, the capability of the organisation to organise the works on time etc. In turn, the volume of M&R actually realised influences the quality of the infrastructure. In principle, the quality will be improved, although it can also partially deteriorate the structural quality; e.g. tamping leads to more fine particles (‘fines’) in the ballast.
Variables represented in model-based Life Cycle Cost DSS

Internal variables
Figure 4.2: General factors influencing the costs and performance of the rail infrastructure
The quality of the work implementation (accuracy) is also often an important factor. Costs of performed M&R depend on all kinds of factors, such as the possibilities to cluster works (effects of scale and scope), the time of day, the duration of possessions, and actual market prices and conditions. Given that all planned M&R works are necessary, a restriction in realising M&R can lead to quicker asset deterioration; the IM or infrastructure owner then contributes to additional costs of ownership (in the near future) by its inaction.

The amounts of preventive and corrective M&R performed account entirely for the running life-cycle costs of the infrastructure. If preventative tasks cannot be performed in non-operative time, they need possessions that reduce the level of availability and reliability in the event of possession overruns. Temporary speed restrictions may also be necessary after some works, which can cause train delays.

Corrective M&R work during the timetable usually results in significant traffic disruption, causing train delays and cancellations, extra costs of operation (planning efforts, staff hours, and buses to replace services) and lost revenues. Repetitive bad performance will result in lost goodwill from the end-users (passengers and shippers). The degree of disruption is not only the result of infrastructure breakdowns and planned possessions, but is also influenced by the track layout (e.g. availability of crossover switches) and the traffic density (maximum train speeds, distribution of speeds, and the mix of passenger/freight traffic).

The drafted process results in overall levels of ownership costs, availability and reliability, the effect variables, in combination with other input factors, such as interest rates and performance payment regimes (penalty rates for the IM). These effect variables form the primary interest, which is reflected in the positioning of the DSS in Figure 4.2. The DSS estimates those effect variables, using input on initial quality levels and degradation rates, amounts of construction work, time-based minor inspection and maintenance needs, plus external conditions, such as financial regimes and transport concepts. As such, the aim of limited model complexity could be satisfied; caution would only be needed in using and interpreting models for estimating the impacts of traffic disruption (see Sections 4.3.5 and 4.3.6).

The DSS calculation steps, which can be distilled from the conceptual model, are presented in Figure 4.3 on the next page (see rectangular boxes). The figure also shows data needed for the calculations (see left and right sides). The dotted, horizontal arrows indicate the use of data from the data-tables for the calculation, while the vertical arrows indicate the sequence in the calculation steps. One or more models, consisting of sets of formulae, can be used for each step; these are discussed in the following subsections and are illustrated with some plots showing intermediate (fictional) output. Note that the formulae are shown in their simplest form; they are often extended in the computerised versions (discussed later) to cover more detailed input.

4.3.2 Step 1: Estimating the loads on the infrastructure

Quality degradation can be modelled as the loss of quality per unit of time or load; loads on the infrastructure elements can be expressed in terms of cumulative tonnage, the number of train passages, or cumulative maintenance interventions (e.g. times of track tamping). With
the help of UIC Leaflet 7.14 [UIC, 1989], a uniform gross tonnage, known as notional (or fictive) tonnage, can be calculated for any railway environment that incorporates impacts from different speeds, axle-loads and wheel diameters.

Data is necessary on the number of trains per day, the types of trains and locomotives, and the average number of train-sets in a day (e.g. trains during peak hours will be longer than off-peak trains). One of the input tables is therefore a reference timetable that can be specified for different periods (years) in order to include forecasted traffic growth or decline.

This timetable is not only needed for estimating traffic loads, but also for calculating scheduled journey time (SJT) on the analysed railway line section. SJT is the sum of journey times for all trains in a specified time interval and can be used in performance payment regimes as a basis for calculating the infrastructure performance (see Chapter 5 for an example). The reference timetable should also include the average agreed time windows, or slots, for planned maintenance. Some necessary formulae are explained in Table 4.4.

![Figure 4.3: Structure of the LifeCycleCostPlan DSS](image-url)
Table 4.4: Basic formulae for estimating loads on the infrastructure

<table>
<thead>
<tr>
<th>No.</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>( T_r(y) = 365 \cdot \sum_THP_r(y) \cdot OH_r(y) \cdot S_r(y) \cdot W_r )</td>
</tr>
<tr>
<td></td>
<td>The annual (real) tonnage, ( T_r ), is the product of the daily traffic on the track (number of trains per hour per track, ( TPH )), the weights of the train-sets (( W )), the average number of train-sets (( S )), and the operational hours per day (( OH )) for all train types (( t )). In the case of seasonal traffic, the number of days per year (used as a basis to calculate the annual tonnage) is less than 365. It may also be necessary to treat locomotives separately.</td>
</tr>
<tr>
<td>4.2</td>
<td>( T_{\text{CUM}}(y) = T_{\text{CUM}}(y-1) + T_r(y) )</td>
</tr>
<tr>
<td></td>
<td>The cumulative tonnage, ( T_{\text{CUM}} ), is an important indicator for the residual life of the infrastructure, as discussed in the following table. It is simply the sum of the annual tonnage carried since the Base Year (( y=0 )).</td>
</tr>
<tr>
<td>4.3</td>
<td>( T_f = T_p \cdot \frac{V_{\text{MAX}}}{} + T_g \cdot \frac{P_g}{18D} )</td>
</tr>
<tr>
<td></td>
<td>Members of the International Union of Railways use the so-called notional tonnage, ( T_f ), in order to compare operational conditions on any railway line. It can therefore be a more useful variable than the real tonnage in the case of mixed passenger (( T_p )) and goods traffic (( T_g )). Input parameters are ( V_{\text{MAX}} ), the maximum permissible speed, ( P_g ), the maximum axle-load of the freight train with wheel diameter ( D ), which is the minimal wheel diameter used.</td>
</tr>
<tr>
<td>4.4</td>
<td>( SJT(y) = 365 \cdot \text{TRACKS} \cdot \text{OH} \cdot \sum_THP_r \cdot JT_r )</td>
</tr>
<tr>
<td></td>
<td>The scheduled journey time (( SJT )) can be used as a basis for calculating infrastructure reliability (see Chapter 5). In this formula, the SJT is calculated for both directions together, as ( JT ) is the journey time for a single train on the considered line section, and TRACKS the total number of tracks.</td>
</tr>
</tbody>
</table>

4.3.3 Step 2: Estimating the periodic maintenance volume

Periodic M&R activities, usually with intervals of more than a year, can be estimated for each major infrastructure component on the basis of the forecasted loads to be carried by the infrastructure. The initial quality level, the deterioration rate and the maintenance or renewal thresholds (i.e. the intervention levels) need to be known in order to estimate these M&R intervals. Maintenance thresholds or limits can be specified in terms of infrastructure parameters or, more straightforwardly, in calendar-based or tonnage-based thresholds. As an example, a head-hardened rail has a lower wear rate than a standard rail. If rail wear is the determining factor for renewal, in curves or in heavy loading environments, this rail will carry more tons. Although the limit of allowable rail wear is maybe equal for both rail types, the allowable tonnage is greater for the head-hardened rail. The initial quality can also be denoted in either a physical quality level or, less refined, as a designed residual life.

When using the DSS design users need to remember that thresholds and carried loads usually differ for different segments of the same line section, as different materials will have been installed at different times and sometimes carry different traffic loads. Hence, residual lifespans and the timing of major M&R are only valid for distinguished, homogeneous infrastructure segments.

It is also possible that the quality deterioration processes of different components are interrelated, either through physical relationships or a conscious policy of harmonising the
maintenance of components in time and space. Figure 4.4 shows an example of a possible dependency in the quality of track geometry. As a result of rail renewal, the entire structure is being replaced and tamped; both standard deviation of the track and rail wear are set to the initial level.

![Graphs showing rail wear and standard deviation of top](image)

**Figure 4.4: Deducting M&R intervals from quality parameters**

Based on the estimated residual lifespans and intervals for performing major M&R, the required rough number of work shifts over the years is calculated for each of the M&R activities (see Table 4.5 on the next page). Within the DSS, the effect of limited resources such as budgets, possessions, and machines, can be simulated by distributing the maintenance works over defined time intervals (in years). As such, the required number of work shifts in a single year is calculated for all periodic M&R. Additional input data is needed, such as the duration of available track possessions and productivity figures for each activity (net productivity rates and set-up/close-down times). Figure 4.5 shows the graphical format of the output.

![Graph showing number of shifts over years](image)

**Figure 4.5: Plot of intermediate output after step 2 (hypothetical case)**
Table 4.5: Basic formulae for estimating the periodic maintenance volume

<table>
<thead>
<tr>
<th>No.</th>
<th>Formula</th>
</tr>
</thead>
</table>
| 4.5 | \( T_{CUM,Z}(y) = T_{CUM,Z}(y-1) + T_{Z}(y) \) with \( T_{CUM,Z}(0) = CL_z \)  
\[ \text{If } T_{CUM,Z}(y) \geq ML_z \text{ then } f_z(y) = f_z(y-1) + 1 \]  
The cumulative tons carried by a particular part of infrastructure (z) are the dominant factor causing (track) degradation. In contrast to Formula 4.2, this formula includes the history of z, i.e. the loads already carried in the Base Year, CL_z, and the ‘life-cycle phase’, f_z is an artificial factor which can be set to indicate that, after specific maintenance limits, a new phase is reached with different levels of spot maintenance. Once a component is renewed, an entire new cycle starts (see Formula 4.7). |
| 4.6 | \( QI_z(y) = QI_z(y-1) - \Delta QI_z \cdot T(y) \) with \( QI_z(0) = UL_z(0) \)  
Instead of using the cumulative tonnage as an indirect indicator, one or more quality indicators can also be used to determine the condition of the infrastructure element and thus the moments for periodic maintenance and renewal. \( UL_z(0) \) is the upper level of the quality indicator. The quality indicator, \( QI_z \), can be indirectly related to the tonnage, as the formula shows; a linear relation is assumed here. An average degradation rate \( \Delta QI_z \) needs to be estimated, defined as the quality loss per carried ton. |
| 4.7 | \( T_{CUM,A}(y) \geq TH_A(0) \) (tonnage threshold) or \( QI_A(y) \leq TH_A(0) \) (quality threshold) then \( A_A(y) = 1 \) and \( QI_A(y+1) = UL_A(f) - \Delta QI_z \cdot T(y) \)  
\[ \text{If } A \text{ is a renewal activity then } T_{CUM,A}(y+1) = 0 \text{ and } f_A(y+1) = 1 \]  
Once the set threshold \( TH \) for a periodic maintenance or renewal activity \( A \) is passed, this activity is initiated for the applicable year (value is set to 1). The corresponding quality indicator is reset to the \( UL(0) \) level. \( UL \) is the upper level of the quality indicator, which is dependent on the life-cycle phase of the infrastructure element: e.g. the geometry of an older track structure, even after maintenance, cannot compete with the initial track quality \( UL(0) \) of a newly laid track. If the infrastructure element is renewed, a new life cycle commences. |
| 4.8 | \( A_A(y) = 1 \) then \( A_A(y) = 1 \)  
The initiation of a particular M&R activity \( A \) possibly also leads by default to another activity \( x \); e.g. the Infrastructure Manager can have a policy to harmonise the renewal of ballast and sleepers. |
| 4.9 | \( A_A(y) = 1 \) then \( QI_A(y) = QI_A(y-1) - \Delta QI_z \cdot T(y) - QL(A_A) \)  
The performance of a particular M&R activity \( A \) can also have cross-impacts on the quality of another infrastructure element \( x \); e.g. track tamping might lead to a quality loss \( QL \) of the ballast bed. |
| 4.10 | \( A_A(y) = 1 \) then \( RQ_A(Y) = Q \cdot \frac{P_s}{n} \) for \( y=Y \) until \( y=n \)  
A quantity for renewal, \( RQ_A \), is selected in a particular year \( Y \) for the activity \( A \), out of the total quantity \( Q \) (e.g. total track length), given the fact that the tonnage \( T \), or quality level \( QI \), has passed the set threshold \( TH \). As an example, if \( P \) is 0.50 for ballast cleaning, then half of the total ballast can be reused. |
| 4.11 | \( RS_A(y) = \text{roundup} \left( \frac{RQ_A(y)/PS_A}{DUR(y) - TL_A} \right) \)  
The number of hours needed for periodic maintenance (calculated as a whole number) is determined by the production speed \( PS \). They depend on the duration \( DUR \) of the provided slot. For each shift, time is lost due to work set up and finishing \( TL \). |
4.3.4 Step 3: Estimating maintenance costs and possession hours

Once the work shifts per year are known, the total costs for periodic maintenance can be calculated, using data on unit costs of fuel and materials (per kilometre) and unit costs of manpower and machines (per work shift). Resulting possession time and speed restrictions are also deducted. Required speed restrictions for particular M&R works can be included in different formats (days, hours, or number of train passages). These can be necessary in order to gradually expose the infrastructure to the (dynamic) traffic loads after maintenance; the speed limit may therefore be lifted in a number of steps. Note that M&R work that is performed in the ‘natural gaps’ of the timetable is not disruptive.

The impacts of small maintenance and failures are also added during this step. Amounts of minor maintenance and failure repair are partly related to the cumulative tonnage or years in service of the infrastructure components and are partly independent from traffic load (e.g. time-based inspection intervals). Since minor maintenance and failure repair consists of a variety of tasks and failure types, summarised estimates are, in the first instance, used as input. The FMEA technique discussed in Section 3.4.5 is useful in collecting required input data, if maintenance concepts and aggregated data on the maintenance processes are absent. Resulting costs, possession and speed restriction hours can be included per ton carried or per year. The regime for minor maintenance needs to be studied in order to include planned possessions correctly; they can often be performed in non-operative hours or, in the Netherlands, included in a monthly maintenance schedule.

The impacts of the periodic M&R and the ongoing maintenance and failure repair can now be combined. Table 4.6 on the next page discusses the required formulae for this third calculation step and Figure 4.6 shows the graphical format of the output.
### Table 4.6: Basic formulae for estimating maintenance costs and possession hours

<table>
<thead>
<tr>
<th>No.</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.12</td>
<td>[ RC_A(y) = RS_A(y) \cdot CS_A(DUR) \cdot (P_{day} + P_{night} \cdot CI_{night}) + RQ_A(y) \cdot (CM_A - RV_A) ]</td>
</tr>
<tr>
<td></td>
<td>The costs for periodic maintenance (RC) are calculated by multiplying the number of shifts (RS) with the costs per shift (CS) for the given duration of the track possession (DUR), and by adding the material costs (using the unit costs of the new materials, CM, minus the residual value per unit, RV, of the removed material). The costs of the shifts will be higher if a part (%) of the works (P_{night}) has to be performed during the night, which can be reflected by a cost index for night-time work CI_{night} (daytime work has an index of 1).</td>
</tr>
<tr>
<td>4.13</td>
<td>[ MC(y) = Q \cdot UMC(f) ]</td>
</tr>
<tr>
<td></td>
<td>The costs of ongoing maintenance can be included as an annual cost because they are usually small compared to the costs of periodic M&amp;R. A unit cost (UMC) can be used, for example a cost per track kilometre or per switch, and this can be further detailed to different infrastructure elements (z), or maintenance activities (A) and life-cycle phases (f). It can also be included as a cost per kilometre per ton carried, which will change the formula slightly.</td>
</tr>
<tr>
<td>4.14</td>
<td>[ PH(y) = Q \cdot UCMH(f) + \sum_A RS_A(y) \cdot (DUR_{TPA}(y) - TFH(y)) ]</td>
</tr>
<tr>
<td></td>
<td>[ TFH(y) = 24 - OH(y) ]</td>
</tr>
<tr>
<td></td>
<td>A unit number of hours of corrective maintenance per kilometre or element (e.g. switch), UCMH, can also be included for the possession hours (PH) of corrective spot maintenance. It is possible to make a more detailed split for all kinds of ‘failure profiles’ and frequencies on the basis of an FMEA analysis, which is not included in this formula. Preventive minor spot maintenance can usually be performed ‘after hours’ or within the regular timetable, and it has thus not to be included in PH. In order to arrive at the total possession hours for a particular year (y), the hours for periodic maintenance and renewal are added. These hours are calculated by multiplying the renewal shifts (RS) and the disruptive possession hours per shift; the disruptive possession hours are the duration of the track possession period (TPP) minus the (nightly) train-free ‘after hours’, in which no trains are scheduled.</td>
</tr>
</tbody>
</table>

#### 4.3.5 Step 4: Estimating infrastructure availability and reliability

The first three steps have provided a set of estimates on individual M&R costs as well as planned and unplanned track possessions and speed restrictions over the years. Next, the disruption (in terms of delayed and cancelled trains) should be determined in order to value the cost impacts on the operations side. The reference timetable can be used to estimate this disruption, using either a mathematical or simulation model. The total number of delay minutes is influenced by the availability of passing tracks or alternative routes, the braking and acceleration characteristics of the trains, and the feasible headways (signalling system).

Several methods, some more refined than others, can be used to estimate delay times. Tables 4.7 and 4.8 show the most basic formulae for estimating resulting delay; they were used in a first, rough analysis of delay times on the Dutch high-speed line (see Chapter 5). Their value is limited because they cannot simulate the rerouting of traffic or the ‘knock-on’ impacts of delayed trains, i.e. secondary delays to other trains. They are also only valid under the assumptions that (1) speed restrictions do not result in train service cancellations, (2) unplanned full blockage leads to cancellation of scheduled trains, and (3) the impact of the signalling system on train delay (block length) is small. These assumptions will often be unacceptable and too rough; in that case, more refined mathematical models or simulation
models should be used, which can be loosely coupled to e.g. an Excel-based DSS. An example of an algebraic model is described in Gallmann et al. [2004].

Table 4.7: Basic formulae for estimating infrastructure reliability impacts

<table>
<thead>
<tr>
<th>No.</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.15</td>
<td>[ R(\text{period}) = 1 - \frac{\sum_{\text{days}} \sum_{\text{tracks}} \sum_{w} JTD}{SJT} ] In addition to generating extra costs, failures and maintenance in timetable hours lead to reduced reliability ((R)) of the particular railway line (section). The level of unreliability caused by the Infrastructure Manager is calculated in this formula as the ratio of total delay minutes (journey time deviation (JTD) of all trains) to scheduled journey time.</td>
</tr>
<tr>
<td>4.16</td>
<td>[ JTD_w = \beta_w \cdot TPH_w \cdot PH + \sum_{SR} SRH_{SR} \cdot TPH_w \cdot TD_{w,SR} ] The total journey time deviation ((JTD)) for all trains of a single train type ((tr)) on a single track are a function of the number of full blockages (due to disruptive track possession) and the amount of post-maintenance speed restriction time ((SRH)). Speed restriction hours ((SRH)) are assumed only to result in delays, not in cancellations, due to the exclusion of ‘knock-on impacts’. Each train that passes the spot under speed restriction ((SR)), slows down over a certain length. It obtains a number of delay minutes ((TD)), but does not cause extra delays for later trains. (TPH) stands for the number of trains per hour. If the assumptions mentioned are not realistic for the location, more advanced models need to be developed.</td>
</tr>
<tr>
<td>4.17</td>
<td>[ SRH_{SR,R}(y) = OH \cdot \sum_A DSR_{A,SR} \cdot RS_A(y) ] [ SRH_{SR,M}(y) = Q \cdot DUR_{SR} \cdot USR_{SR}(f) ] Periodic major maintenance and renewal work ((R)) and spot maintenance ((M)) cause speed restriction hours. In the case of (R), speed restrictions are set after performed works ((A)) in order to realise a gradual increase of the load on the newly placed components or tamped track. A number of days at restricted speeds ((DSR)) are sometimes set, with gradually increasing speed limits ((SR)). A correction may be necessary if works take place on adjacent track sections over subsequent days, if speed limitations last more than one day. For the speed restriction hours for corrective spot maintenance, a unit number of speed restrictions ((USR)) per year or per ton can be set, specified to a certain speed limit ((SR)) and (average) duration ((DUR)). Data can be obtained from reliability databases.</td>
</tr>
<tr>
<td>4.18</td>
<td>If (A) is periodic overhaul or renewal then [ L_{SR,A}(y) = (TPP(y) - TL_A) \cdot PS_A + L_{\text{TRAIN}} ] An important variable is the track length to which the speed restriction is applied. In combination with the speed limit applied this will determine the train delay. In the case of spot maintenance, this length is only a short length around the failure and maintenance spot plus the train length, given that the back of the train also still has to run at the set speed limit and the block lengths of the signalling system. However, in the case of (R), the length of the speed restrictions depends on the performed work length per shift ((PS)) that is calculated based on the net productivity ((m/h)) and the hours worked ((TL) is the time lost in setting up and finishing the work).</td>
</tr>
<tr>
<td>4.19</td>
<td>[ TD_{SR,A} = DPT - UPT ] The train delay minutes ((TD)) caused for a single train is the difference between the passing time in the case of the set speed restriction ((DPT_{SR})) with a given length ((L_{SR})) and the usual passing time ((UPT)). For work that is being performed over several kilometres, and with speed restrictions of more than a single day, speed restrictions are applied simultaneously on adjacent track segments, which will reduce the delay time attributable to a single segment. This is not modelled in this formula.</td>
</tr>
</tbody>
</table>
### Table 4.8: Basic formulae for estimating infrastructure reliability impacts (continued)

<table>
<thead>
<tr>
<th>No.</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.20</td>
<td>( DPT = T_{\text{BRAKE}} + T_{\text{SR}} + T_{\text{ACC}} )</td>
</tr>
<tr>
<td></td>
<td>The delayed passing time ((DPT)) is the sum of the time needed for braking ((T_{\text{BRAKE}})), in order to drive at the required speed ((SR)), the time used for driving over (L_{\text{SR}}), and the time to accelerate ((T_{\text{ACC}})) to the usual, maximum permissible, speed.</td>
</tr>
<tr>
<td>4.21</td>
<td>( PL = L_{\text{BRAKE}} + L_{\text{SR}} + L_{\text{ACC}} )</td>
</tr>
<tr>
<td></td>
<td>The passing length ((PL)) is defined (analogous to Formula 4.20) as the sum of the track length needed for braking ((L_{\text{BRAKE}})), the length of the speed restriction ((L_{\text{SR}})), and the length needed for accelerating once the spot has been passed ((L_{\text{ACC}})).</td>
</tr>
<tr>
<td>4.22</td>
<td>( UPT = \frac{PL}{V_{\text{MAX}}} )</td>
</tr>
<tr>
<td></td>
<td>The usual passing time ((UPT)) is simply the time needed to pass the entire length ((PL)) at maximum speed.</td>
</tr>
<tr>
<td>4.23</td>
<td>( T_{\text{BRAKE}} = \frac{V_{\text{SR}} - V_{\text{MAX}}}{\text{DEC}} )</td>
</tr>
<tr>
<td></td>
<td>The time needed for braking ((T_{\text{BRAKE}})) is the ratio of speed deviation (maximum speed minus limited speed) and average braking deceleration ((\text{DEC}, \text{ in m/s}^2)).</td>
</tr>
<tr>
<td>4.24</td>
<td>( T_{\text{SR}} = V_{\text{SR}} \cdot L_{\text{SR}} )</td>
</tr>
<tr>
<td></td>
<td>The train runs at a constant speed of (V_{\text{SR}}) over (L_{\text{SR}}).</td>
</tr>
<tr>
<td>4.25</td>
<td>( T_{\text{ACC}} = T_{\text{ACC}}(0, V_{\text{MAX}}) - T_{\text{ACC}}(0, V_{\text{SR}}) )</td>
</tr>
<tr>
<td></td>
<td>( T_{\text{ACC}}(0, V_x) = \sum_{j=0}^{x} V_j - V_{j-1} \cdot \frac{1}{\text{ACC}_{j-1}} )</td>
</tr>
<tr>
<td></td>
<td>When trains accelerate, a number of acceleration steps can usually be recognised (see Chapter 5 for an example). The time needed for acceleration can be calculated using the formula shown: the time is first calculated for each of the 'speed deviation steps' with a constant acceleration level ((\text{ACC}, \text{ in m/s}^2)). In order to obtain the entire acceleration from speed 0 to (V_{\text{MAX}}), all steps are needed. For (V_{\text{SR}}) fewer steps will be required; the difference in time can thus be calculated, which is the time needed to accelerate from speed (V_{\text{SR}}) to (V_{\text{MAX}}).</td>
</tr>
<tr>
<td>4.26</td>
<td>( L_{\text{BRAKE}} = V_{\text{MAX}} \cdot T_{\text{BRAKE}} - 0.5 \cdot \text{DEC} \cdot T_{\text{BRAKE}}^2 )</td>
</tr>
<tr>
<td></td>
<td>( L_{\text{BRAKE}} ) is a function of maximum speed, braking deceleration and time for braking.</td>
</tr>
<tr>
<td>4.27</td>
<td>( L_{\text{ACC}} = L_{\text{ACC}}(0, V_{\text{MAX}}) - T_{\text{ACC}}(0, V_{\text{SR}}) )</td>
</tr>
<tr>
<td></td>
<td>( L_{\text{ACC}}(0, V_x) = \sum_{j=0}^{x} (V_{j-1} \cdot T_{\text{ACC},j} + 0.5 \cdot \text{ACC}<em>{j-1} \cdot T</em>{j}^2) )</td>
</tr>
<tr>
<td></td>
<td>Analogous to Formula 4.25, the track length needed for accelerating is calculated.</td>
</tr>
</tbody>
</table>

### 4.3.6 Step 5: Estimating total life-cycle costs

The final step is to estimate the overall life-cycle costs for each decision alternative, which requires the monitored impacts of system availability and reliability and the cash flows for initial investments and financing to be known. Additional information is therefore needed, such as the costs of initial investments, interest rates (costs of financing), and costs and (missed) benefits from (disrupted) transport operations.
Cost-benefit models to estimate the impacts of (planned and unplanned) speed restrictions and possessions usually relate impaired damage to the duration of blockage and the affected types of traffic (e.g. intercity, suburban and interregional trains). In other words, a breakdown or speed restriction on a regional, 'low-density' line probably has less severe consequences than on an international high-speed line. IMs may use a regime of penalty rates to reflect those costs and revenues (see Chapters 5 and 6). Otherwise, a model can be based on general guidelines for cost-benefit analysis of transport policy (see Morisugi and Hayashi [2000] for an overview of international practices). Gallmann et al. [2004] provide an example of this approach, in which formulae from Table 4.9 were included. These formulae were developed in a study of ProRail/Railned for planned possessions on double-track routes in the Netherlands; traffic from both directions should be used as input. N.B.: The values mentioned are outdated, as the study was conducted in 1997; the formulae are only included as an example of how disruption by (planned) possessions can be accounted for.

Once the direct and indirect costs of M&R are available, all future costs are discounted to their present value in the Base Year in order to make them comparable (see Figure 4.7 for an impression of the effect of discounting).

![Graph](image)

Figure 4.7: Plot of intermediate output after step 5 (hypothetical case)

Once all costs are expressed in their present value, internal rates of return or annuities (annual equivalent costs) can be calculated for each alternative for defined periods of depreciation. It may be helpful to label a number of highly uncertain events during the construction and operation of the system as special risks, which means that they are shown as separate risk margins on top of the outcomes (annuities); this may give an idea of their cost impact if the event occurs. Figures 4.8 shows the graphical format of the output. Table 4.11 on the next page presents required formulae.
Table 4.9: Examples of formulae for delay impact costs [ProRail/Railned, 1997b]

<table>
<thead>
<tr>
<th>No.</th>
<th>Formula</th>
</tr>
</thead>
</table>
| 4.33 | \[TPD = \alpha \cdot \sum_{v, \text{hour}} PASS_v \cdot TD_v\]  
The total passenger delay (TPD) per hour is the product of the average number of passengers (\(PASS\)) per hour and the average delay that they incur on a particular route. The number of passengers is the sum of the average number of passengers per train (\(tr\)) for all scheduled trains in one hour. Alpha is a factor that has a value of 0.8 (if a planned single-track possession), and 0.6 (if a double-track possession). It expresses the percentage of passengers that still decides to travel by train or by special chartered NS buses. A further distinction between types of passengers (intercity travellers, commuters etc.) is possible. |
| 4.34 | \[TFD = \beta \cdot \sum_{v} WAGONS \cdot TD\]  
The total delay for freight (TFD) per hour is the product of the average number of wagons (\(WAGONS\)) per hour and the total delay per wagon (\(TD\)) on the particular route. Beta is a factor that has a value of 0.95 to 1.00 (for planned single-track possessions), and 0.95 (for double-track possessions); it expresses the number of wagons still transported by train. |
| 4.35 | \[DINC_{\text{pass}} = (1 - \alpha) \cdot \gamma \cdot PASS_{\text{hour}} \cdot DISTANCE \cdot TO_{\text{pass}}\]  
Direct income loss (DINC) for the passenger train operators is caused by a reduced number of passengers. The percentage of no-shows is (1-Alpha) of the normal ‘passenger population’. Further, only half the population buys a ticket (Gamma=0.5), while the other half uses monthly or annual travel passes. If the latter do not travel on that day, this does not result in a direct income loss. The lost turnover can now be calculated by also including the average distance of passengers on the particular route (\(DISTANCE\)) and the turnover per kilometre (\(TO\)); the study used 0.12 euro. |
| 4.36 | \[DINC_{\text{freight}} = (1 - \beta) \cdot WAGONS \cdot FTONS \cdot TO_{\text{ton}}\]  
Direct income loss (DINC) for the freight operators is caused by a reduced number of wagons. The percentage of no-shows is (1-Beta) of the normal number of ‘wagon population’. The lost turnover can be calculated using the average freight tonnage per wagon (\(FTONS\)) and the turnover per transported ton (\(TO_{\text{ton}}\)), which is around 7.5 euro. |
| 4.37 | \[DEC_{\text{pass}} = PASS_{\text{hour}} \cdot \left(\frac{1}{12} + \frac{L_{\text{route}}}{30}\right)\]  
The direct extra costs (DEC) for the passenger operators are the result of using buses instead of trains. This is an indicative formula, only for double-track possessions, valid for an hourly fare for the buses of 45 euro. \(L\) is the length of the route, on which the buses are employed. In the case of single-track possessions, buses are not necessary. |
| 4.38 | \[DEC_{\text{freight}} = \delta \cdot L_{\text{extra}} \cdot WAGONS \cdot FTONS \cdot OC \cdot TO_{\text{ton}}\]  
The direct extra costs (DEC) for the freight operators are the result of rerouting trains. Delta is the percentage of trains to be rerouted, which can be any value between 0 and 1, depending on the situation. \(L\) is the extra length in kilometres to be covered. \(OC\) is the percentage of turnover needed to cover the operating costs; the study assumed 60%. \(TO\) is the turnover: 0.05 eurocents per ton kilometre. |
| 4.39 | \[SEC = \varepsilon \cdot TDP\]  
Finally, the incurred costs for society (SEC) are determined using agreed figures on (economic) travel time values by the Ministry of Transport. For passenger transport the time value, or Epsilon, is 0.085 euro per minute. For freight, Epsilon is 0.344 euro per minute per wagon. TDP was already defined as the total incurred delay per hour. The model assumes that the no-shows have access to other means of transport. |
Figure 4.8: Plot of annuity components (hypothetical case)

The next section will discuss the set up for testing the effectiveness of the decision-support approach, with the DSS prototype as its centrepiece. Note that also qualitative support for estimating input data was developed with the conceptual model. Lists of variables were developed which should assist the engineers in describing the characteristics of a degradation process; Table 4.10 shows an example. A distinction is made between damage features, predicting factors (deteriorating these damage features) and maintenance actions (improving them). If detailed empirical data or engineering knowledge is available, these factors could be included in degradation models.

Table 4.10: Possibly relevant input and output related to degradation of rails

<table>
<thead>
<tr>
<th>Predictors</th>
<th>Quality aspects</th>
<th>Maintenance actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carried tonnage</td>
<td>Rail corrugation</td>
<td>Rail grinding</td>
</tr>
<tr>
<td>Quality of subsurface</td>
<td>Internal rail defects/cracks</td>
<td>Rail renewal</td>
</tr>
<tr>
<td>Wheel defects</td>
<td>Rolling contact fatigue</td>
<td>Changing rail parts</td>
</tr>
<tr>
<td>Speeds and axle-loads</td>
<td>Rail-head wear (gauge corner)</td>
<td></td>
</tr>
<tr>
<td>Environmental conditions</td>
<td>Rail fatigue</td>
<td></td>
</tr>
<tr>
<td>Type of support (ballast/concrete)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curvature/cant deficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rail type (shape, weight, etc.)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 4.11: Basic formulae for estimating the infrastructure life cycle costs

<table>
<thead>
<tr>
<th>No.</th>
<th>Formula</th>
</tr>
</thead>
</table>
| 4.28 | \[
LCC = \sum_{y=0}^{n} \frac{TC(y)}{(1+r)^y} = \sum_{y=0}^{n} \frac{(CC(y) + MC(y) + RC(y) + DC(y) + OC(y))}{(1+r)^y}
\]  
\[
DC = f(R(\text{period}), PR)
\]
\[
DC = DNC + DEC + SEC
\]  
Two steps are needed in order to calculate the entire life-cycle costs. Firstly, all costs during a single year \((y)\) are summed. Next, the present value is calculated for the resulting total cost per year, \(TC(y)\), using the real interest rate \((r)\). This process is iterated for each year of the analysed period. This results in the present value of the life-cycle costs \((LCC)\), and consists of:

- construction costs \((CC)\) can be added as a lump-sum amount of money during the first couple of years; a present value is then required;
- spot maintenance costs \((MC)\) and periodic maintenance and renewal costs \((RC)\);
- delay costs \((DC)\) are the result of the delivered reliability \((R)\) and the cost consequences of the delay minutes produced (lost revenues and increased operating costs). The penalty rates \((PR)\), prescribed by the performance payment regime, reflect the consequences. Otherwise, a cost-benefit model needs to be developed to estimate the direct income loss of the operators \((DINC)\), the direct extra costs for using buses or rerouting traffic \((DEC)\), and the societal extra costs \((SEC)\). DINC may also include goodwill costs;
- organisational costs \((OC)\) are the annual flat costs required for inspection and the maintenance planning and incident response organisation; they should only be included if they deviate from the different decision alternatives.

| 4.29 | \[
ANN(LCC) = \frac{(1+r)^n \cdot r}{(1+r)^n - 1} \cdot LCC \text{ or } ANN = \sum_{y=0}^{n} ANN(TC(y))
\]  
The annuity \((ANN)\), or annual equivalent cost, is calculated with all present values of LCC. In other words, the performance fee is the amount of money required each year for depreciation and interest payments in order to finance the LCC.

| 4.30 | \[
PF_A = \sum_{y=0}^{n} ANN(TC(y)) \cdot \frac{TC_A(y)}{TC(y)}
\]  
This formula calculates the part of the performance fee that can be assigned to a specific activity \((A)\), which is helpful for identifying key cost drivers.

| 4.31 | \[
DC_A = \sum_{y=0}^{n} DC(y) \cdot \frac{\sum_{v} \sum_{SR} JTD_a}{\sum_{v} \sum_{SR} JTD}
\]  
Progressive penalty rates are being used in some performance regimes, such as the Dutch HSL. The consequence is that penalties cannot be assigned directly to individual sources of unreliability. The penalties for the entire infrastructure system first have to be calculated based on the total delay minutes during a specified period. Formula 4.31 can then be used to assign delay costs to specific sources of unreliability \((A)\).

| 4.32 | \[
DEBT(y) = (DEBT(y-1) + TC(y) - PF) \cdot (1 + r)
\]
\[
FC = \sum_y FC(y) = \sum_y \frac{DEBT(y) \cdot r}{1 + r}
\]  
This formula shows the costs of financing separately; the financing costs \((FC)\) are calculated based on the outstanding debt \((DEBT)\).
4.4 Conclusion and approach to testing the decision-support approach

This chapter studied the policy science literature for ways of influencing decision-making in multi-stakeholder settings and developed a particular approach for encouraging 'life-cycle thinking' in decision-making processes in the railway sector. The main conclusion is that an LCC exercise, outside of the real-life design and maintenance processes, would have a slim chance of success in improving the quality of decision-making. It was decided to develop a simple DSS prototype for estimating railway life-cycle costs as the centrepiece of this 'LCC-based decision-support approach', with the author as DSS chauffeur.\footnote{LCC was already adopted in Chapter 3 as a method with a high chance of success for the rail sector.} The DSS prototype should be easy to modify, depending on the specific needs of decision makers, and can be deployed in a participative analysis process, thus dealing appropriately with the dynamic character of tactical and strategic decision-making processes. Stakeholders around the decision-making process need to be involved in this process as much as possible, in order to include their viewpoints and to develop a commitment to life-cycle based strategies. A set of criteria was derived from Thissen and Twaalhoffen [2000] for determining the success of the decision-support approach in influencing the decision-making and allowing more life-cycle-based strategies to be developed (see Section 4.1.3, Table 4.2).

Having all these ingredients available, an answer to the last question of this study can be pursued: Is a decision-support approach able to have courses of action developed and adopted, which are expected to be more cost-effective (over the system life-cycle)? As discussed in Section 1.3, it was decided to search for real-world case studies for testing the decision-support approach. First, a pilot study was performed in 1998, in order to study whether this first DSS prototype met the demands of a real-world case. This pilot study was performed for the Autonomous Community of Madrid and was described in Appendix D. The author partly implemented the DSS structure of Section 4.3 in a DSS prototype, based on Microsoft Excel, which was called LifeCycleCostPlan. The DSS prototype seemed suitable for assessing alternative infrastructure designs and seemed to allow the analyst to play a clear role in the decision-making process, i.e. providing quantified life-cycle cost expectations for specific future scenarios. The pilot study confirmed problems with the availability of maintenance data, requiring specialist support in the collection of input data.

It was considered important that potential cases (for testing the approach) were direct requests from managers in the field; this would guarantee a real interest in life-cycle cost analysis. Time was taken to select new case studies in the Dutch railway sector, while gaming was a 'last resort option'. Cooperation was established with parties in the Dutch and European rail sector. Three main criteria were set for selecting case studies.

1. The problem owners express their support in guaranteeing the provision of required expertise, data and other resources in their organisations.
2. The problem owners express their commitment to perform the analysis in an independent, scientific manner and to seriously back such an approach.
3. The problem owners guarantee that the process can be evaluated afterwards through anonymous interviews with the participants and official documents, to the extent needed to analyse the effects of the support provided.

An answer to the third research question would thus be pursued through ‘action research’, in which the author would both be practitioner (of the decision-support approach) and observer of the result. It was decided that the evaluation should therefore only be based on official documents and produced artefacts (minutes of meetings, intermediate reports, delivered decision-support tools) and an ex-post evaluation through structured interviews with the participants as well as more distant decision-makers. The author would reconstruct the process course and the analysis results, using these documents, while ex-post interviews were selected as the primary source of information, because they could best reveal the way that the decision support worked out in the decision-making process. The list of questions consisted of both open, qualitative questions and questions in which the participants’ scores were required. These quantitative questions were linked to the success indicators from Section 4.1.3. An implication of using interviews would be that the findings would be the (absence of) success as perceived by the interviewees’ population. A potential drawback is that interviewees express too optimistic or pessimistic views. This can be partly resolved by analysing whether the findings match with the aforementioned process reconstructions, which can also include the period after the interviews were held. If verification is not possible, it will be stressed that the findings concern the participants’ views.46

This approach resulted in three case studies being completed (see Section 1.3), of which the first two are discussed in Chapter 5; these concerned an assessment of track designs for the HSL South line and an integral review of the HSL South rail system design and maintenance strategies. The ex-post evaluation of the effects of the LCC-based approach in all case studies is reported in Chapter 7. Chapters 5 and 6 include reconstructions of the decision-making processes, their context and the provided decision support (e.g. objectives, assumptions and delivered reports). They are a crucial part of this research, because they allow verifying outcomes from the ex-post interviews (see Chapter 7) and guarantee the reproducibility of the research.47 Chapter 7 uses the (cross-case) evaluation to formulate conclusions on the effects of the decision-support approach. It is already noted here that conclusions are formulated cautiously; findings from only one case study are treated as preliminary [Yin, 1989].48

46 Notice that it was thus not a criterion that the problem owners would provide their (confidential) cost data, as the test would focus on the way that the LCC findings influenced the decision-making process. Data on the LCC analysis process, its findings, and the impacts on the decision-making were, however, required to be available, including all statements made afterwards by the interviewees. Results from the performed life-cycle cost analyses are therefore only included in Chapters 5 and 6 (or in appendices) as part of the process description, and are not used to recommend 'best' design and maintenance practices.

47 The discussed cases could be ‘re-played’ in a laboratory setting through gaming (see Section 1.3).

48 See Flyvbjerg [2004] for an interesting present-day view on case study research.
5. Cases 1 and 2: Design of the HSL South

This chapter discusses two different case studies that were performed within the context of the Dutch 'High-Speed Line (HSL) South' tender in 1999 and 2000. The Infrastructure Provider Contract was previously mentioned in Section 2.2.1 for its innovative approach: bidders were asked to construct and finance the HSL’s rail system and ensure adequate quality during the first 25 years of operation. Sections 5.1 and 5.2 are used to introduce this context in more detail. The two case studies are then described in Sections 5.3 to 5.6. The aims and chosen work approach are discussed first, followed by the course of the study process and the outcomes. Finally, Section 5.7 reflects on the issues that were at stake in the track selection process. Note that the evaluation is included in Chapter 7.

5.1 The Dutch high-speed line

High-speed rail makes up a growing part of the market, and has expanded considerably since it first gained ground in Europe in the 1980s (the Paris-Lyon route). HSL lines are currently being constructed across the EU as part of the envisioned Trans-European High-Speed Network. New lines are built for speeds over 300 km/h, whereas selected parts of the existing networks are being upgraded for speeds over 200 km/h.

The construction of the HSL South is part of the Trans-European Network plan and is also the first experience in the Netherlands with high-speed rail (see Figure 5.1 for its route alignment). HSL South, further referred to as ‘the HSL’, forms the Dutch part of the high-speed link from Amsterdam to Brussels and Paris; however, it will also provide rapid access to the southern part of the Netherlands via the city of Breda. Journey times and route capacity will improve considerably thanks to its new route between Rotterdam and Amsterdam and the high-speed limit of 300 km/h. Journey times between the central stations in Amsterdam and Rotterdam will be 36 minutes (including a stop at Schiphol airport station), instead of the current 62 minutes (see Figure 5.2 for the speed-distance graph). The journey time between Amsterdam and Brussels will be 1.5 hours, saving more than 1 hour, according to the Invitation to Consult (ITC) [HSL Project Organisation (PO), 1999a]. Travelling from Amsterdam to Paris Gare-du-Nord station will take only 3 hours and the trip to London Waterloo only 3.5 hours, provided that the high-speed routes in Belgium and the UK are also in use.
Figures 5.1 and 5.2 show that two different sections exist along the HSL route, which together comprise a length of around 100 kilometres. Trains from Amsterdam will enter the northern section (known as HSL RA) at the town of Hoofddorp, after Schiphol airport. They re-enter the conventional rail network at Rotterdam. A few kilometres after Rotterdam station, they return to the southern high-speed section (HSL BR). Maximum speed will be 300 km/h for international trains (see Figure 5.2) and 220 km/h for domestic trains [HSL PO, 1999a].

![Schematic HSL South route map](image)

**Figure 5.1: Schematic HSL South route map**

![HSL South speed-distance graph](image)

**Figure 5.2: HSL South speed-distance graph**
The HSL system, which is due to open in 2007, is designed to accommodate 15-20 million passengers by 2015, according to the ITC\textsuperscript{49}; the HSL Sections will provide a minimum headway of 3 minutes and maximum capacity of 16 trains per hour. Further capacity increases (up to 30 million passengers annually by 2035), are envisioned possible [HSL PO, 1999a, Appendix 3]. In addition, high punctuality levels are aimed for. The government stated in the ITC [HSL PO, 1999a, Appendix 3] that: ‘the system will aim to obtain a level of train punctuality that is superior to other comparable high-speed train services in Europe’. A concession for operations during the first 15 years was granted to the High-Speed Alliance, a consortium consisting of the Netherlands Railways (NS) and Royal Dutch Airlines (KLM)/Air France. They will implement the Dutch share in the services to Brussels and beyond.

The HSL was a long-debated project, particularly the route alignment through the Green Heart, a protected polder landscape in the middle of the Randstad (‘Rimcity’), the urban conglomeration that comprises Amsterdam, The Hague, Rotterdam and Utrecht. In 1991 the Government presented the first route proposal, which was finalised in 1998 after having passed all statutory procedures. Subsequently, the government-commissioned HSL South Project Organisation started working on the engineering, procurement and construction tasks. The project was performed under the direct responsibility of the Ministry of Transport, in contrast to other railway construction projects. The Project Organisation (otherwise referred to in this chapter as the ‘State’ or the ‘Client’) was staffed by the Ministry of Transport, two Dutch engineering consultants plus ProRail/RIB personnel.

The high-speed rail system will need strict design, maintenance and safety regimes. For example, the State demanded that tracks must not deviate by more than 4 mm from their calculated path over a length of 20 metres [HSL PO, 1999d]. An important design choice was therefore to place 60 kilometres of track on a concrete substructure with piled foundations on sand layers 30 metres below the surface [Russel, 1999]. Although the initial design already contained large civil structures, the main reason for this drastic decision was the marshy ground in this part of the Netherlands. Apart from ongoing geometric maintenance needs or even serious settlement problems, there is a serious risk of trains approaching the ‘critical speed’, where the pressure waves that it creates travel faster than the train itself. The resonance between track and train can lead to reduced riding comfort and ultimately derailment [see Esveld and De Man, 1996]. Other countries, such as France, have had problems with marshy grounds, but only for a few hundred metres; there it was decided to excavate the poor soil and replace it with rock, but this was not deemed a realistic option for this project [Russel, 1999]. Figure 5.3 on the next page gives an impression of the resulting structure, which the State referred to as ‘the settlement-free substructure’.

The construction of the HSL had a projected cost of € 4 billion (in 2000); the project would be tendered through seven large contracts [HSL PO, 1998].\textsuperscript{50} Four contracts, covering different geographical areas, had been drawn up for the substructure, while one contract had been drawn up for a 7.5-km shield-driven tunnel under part of the Green Heart, and another

\textsuperscript{49} At the time of the tender, the opening date was still scheduled for 2005.

\textsuperscript{50} At the start of the project, in 1992, the projected costs were € 2.3 billion [Netherlands Court of Audit, 2003]. The current cost estimates are € 6.7 billion [www.bouwweb.nl, April 14].
contract had been drawn up for the connections to the conventional network. Finally, there was the Infrastructure Provider (IP) Contract for the 'superstructure' or 'rail system', mainly consisting of tracks, sound barriers, power supply, command, control and communication (CCC) systems.

![Impression of HSL South substructure (including clearance profile of the train)](image)

**Figure 5.3: Impression of HSL South substructure (including clearance profile of the train)**

The tendering of the IP contract was realised through a number of steps [HSL PO, 1999c]. First of all, four 'most suitable' tenderers were selected from a list of respondents during a Prequalification Stage. The selection criteria included their capacities relating to project management, technical competence (systems engineering, railway engineering, safety management, and maintenance management), plus their financial position. Only consortia of large companies with sufficient financial backing were therefore able to participate, since the projected capital investment was in the order of € 700 million. Four qualified consortia received the ITC, which contained the tender guidelines and a draft Implementation Agreement. These tenderers were invited for the Bidding Stage. This stage comprised three phases, namely the Consultation, Tendering and Negotiation Phases. During the Consultation Phase the State consulted the tenderers on technical, contractual and costing matters through a series of official meetings. In the Tendering Phase the tenderers were required to submit a Base Tender that was fully compliant with the State’s requirements; they were also allowed to submit a number of Alternative Tenders that would provide better value for money. After this phase, two tenderers received an Invitation to Negotiate (ITN). Finally, the preferred consortium was granted a period of exclusivity in order to conclude a Best and Final Offer and to reach financial agreement with its lenders. During this process the State had reserved its right to set up a traditional tender using state funding, should the tenderers prove to be too expensive.

According to the Invitation to Tender (ITT), the selected IP would be paid a so-called 'performance fee' each trimester for the first 25 years of operation (the Availability Period). This performance fee would eventually cover expected construction and management expenses, and the net present value of the total fee was expressed as being the foremost metric in the selection of the IP [HSL PO, 1999c]. A guarantee period of 5 years would be applied afterwards, with the IP having to pay for the recovery of serious infrastructure faults. The performance fee had to cover all risks relating to the construction and commissioning of the
system, interest rates, inflation, costs of substructure maintenance, plus timing and costs of M&R. However, the IP would be protected from a number of risks, such as the timely completion of the substructure, force majeure events (such as floods), and discriminatory changes to the law. Finally, the State had formulated a number of exceptional events that could change its obligations. Clause 4.1.2 of the ITC stated that the State was entitled to terminate the Implementation Agreement if the 84-day rolling availability average fell below 90%, while Clause 6.3.5.1 stated that the IP was only entitled to 30% of the performance fee if only one HSL Section was commissioned for operation on the agreed date. The IP to be selected would become responsible for designing, building, financing and maintaining the rail system. The State had put forward a performance payments regime (PPR) to provide an incentive for the IP to create a reliable transport system. This is discussed in the next section.

5.2 The proposed performance payment regime

The State developed a PPR on the basis of 'no performance, no fee' and 'to hurt, but not to kill' in the event of poor performance [Ochtman, 1999]. According to the PPR, performance would be measured in terms of train delays and cancellations, asset condition and cleanliness. These last two are determined during audits and compliance demonstrations, but are much less serious than timetable adherence, on which this section focuses. A so-called performance payment mathematical algorithm (PPMA) attributes penalties to the IP on the basis of a calculated 'availability level', i.e. the ratio of total train delay minutes and total scheduled journey time on the HSL IP sections during the specified measurement intervals. Train delay is defined in Formula 4.16 as journey time deviation (JTD); a standard delay time of 180 minutes is applied for cancelled trains. The ratio is referred to by the State as the 'system availability', which is a confusing term. Reliability would be the correct term, because the calculation focuses entirely on interruptions of train operations due to infrastructure failures or unplanned possession overruns; nevertheless, this section continues to use the term 'availability' in order to speak the same language. During the availability period the IP would be granted a nightly free 4-hour slot in which to carry out maintenance on a single track and (once every 14 days) a slot for both tracks at the same time. The State had already developed a detailed reference timetable for the HSL.

Although the performance fee was stipulated on a quarterly basis, availability would be calculated on a daily and four-weekly basis. If availability on a particular day was below 90%, than that day would be considered a non-available day (NAD) and no performance payment would be granted for that day. In addition, availability is calculated for 13 'performance periods' per year. Should availability fall below 99% during one of these periods, the agreed performance payment would be reduced by penalties according to a progressive regime. The basic penalty rates range from 500 euro per minute for delay minutes in the interval from 99% to 96% availability, to 3,500 euro per minute for the interval between 92% and 90%. It is worth mentioning that a so-called 'frequency ratio' was also included in the PPMA; a compensation factor to make the penalty level immune to changes in traffic. This means that the actual rates to be paid per minute are often lower than the aforementioned rates; this is illustrated in Figure 5.4. The figure shows that penalty rates are halved if train services are doubled (in this case from 50 to 100 scheduled minutes per month), resulting in the same penalty level for the same realised availability.
The basic principle behind the PPR is that the Infrastructure Provider is only judged on its own actions or faults, which is why availability is not calculated on the basis of actual delay times (which are also influenced by third-party behaviour). In order to realise this principle, the State asked each tenderer to develop a prototype performance simulation model (PSM) for estimating delays in the event of infrastructure failures. This PSM should 'simulate the system and emulate failure and recoverability scenarios' on the basis of the fixed timetable [HSL PO, 1999a]. In determining the number of delay minutes attributable to the Infrastructure Provider, a standard 'delay recovery period' is deducted for each of the delayed trains, 'prior to the commencement of subsequent journeys to that on which the initial delay was incurred' [HSL PO, 1999a, Clause 5.7]. Box 5.1 shows an example.

**Box 5.1: Example of train delay attribution (taken from the ITC, HSL P.O., 1999a, modified)**

Domestic train no. D01C travelling from Amsterdam to Breda is delayed by a failure scenario on the northern section. It is scheduled to exit the Section at Km 2.39 at 06.46 hours, but actually exits at 07.01 hours. This delay of 15 minutes is recorded. The PSM will then simulate the following:

Train D01C continues 15 minutes behind schedule, so that it arrives and departs Rotterdam CS at 07.04 and 07.06 hours respectively, and then continues in order to pass the exit of the southern section at 07.19 hours, still 15 minutes behind schedule. A second delay of 15 minutes is recorded. The train is due to make a return journey to Amsterdam at 07.49 hours. It should thus depart at 08.01 hours (15 minutes delay minus the delay recovery period of 3 minutes). Two further delays are recorded as the train exits the northern and southern sections on its journey to Amsterdam.

Train D01C is scheduled to make further journeys between Amsterdam and Breda. Delays of 9, 9, 6, 6, 3, and 3 minutes are recorded as the train exits each successive HSL Section on subsequent journeys. By the end of the fifth journey all of the delay minutes have been recovered and train D01C departs Breda on time at 13.49 hours. In total, the train has incurred 66 minutes of delay that is attributable to the Infrastructure Provider. Had the initial delay been 20 minutes or more, then the following trains would also have been affected and the respective simulated delays to these trains would be calculated in the same manner as described above.

It was soon clear that the Infrastructure Provider contract, including the proposed PPR, presented a serious challenge for any consortium preparing a bid for becoming the responsible IP. The following two sections discuss the first case study that the author performed at one of
those consortia. The particular consortium roughly consisted of a special-purpose company (SPC), or working group at that time, which would steer two different companies (still working groups at that time), i.e. the Engineering, Construction and Procurement Company (EPC) and the Maintenance and Renewal Company (M&R-Co). 'Life-cycle cost management' had been positioned in the organisational chart as a task for the M&R-Co and this author in particular.

5.3 Assessing high-speed track designs – aims and approach

The Consultation Phase took place in the summer of 1999; after receiving the ITC, the consortium immediately started to develop an opinion on the proposed arrangements for risk allocation, maintenance slots and performance payments. A number of staff members were appointed to formulate this opinion and to express it in meetings with the Client. Other staff members, including the author, were appointed to analyse the ITC requirements and to develop feasible design and maintenance solutions. They therefore provided input for the staff members who were preparing the consultation meetings.

A remarkable aspect of the project was the prescribed use of innovative technology. The State wanted to realise a state-of-the-art ‘21st century railway’, in line with the European developments. With regard to the power supply and signalling, the technologies to be used for the subsystems were prescribed: a 25 kV power supply system and a signalling system that would be compliant with level 2 of ETCS.\(^{51}\) A track system was not directly imposed, but the design constraints (e.g. height allowed) implicitly required embedded rails or directly fastened slab track. Representatives of the State also stressed in meetings that ballasted track was considered a non-viable option.

The selection of a suitable track system gave rise to much discussion within the consortium. The partners and potential lenders considered the systems that met the Client’s demands, particularly the embedded rail system (ERS), to be unproven technology for high-speed traffic. Moreover, the tracks would be by far the most costly investment, which is why all partners actively intervened in the selection. They had different expectations concerning the performance of these track systems and a significant partner in the consortium favoured ballasted track.

After a period of investigation, which had already begun some time before the Consultation Phase, the EPC Track group had selected four track structures (with ballasted track) as a kind of reference system (see Figure 5.5). The main advantages of ballasted track are its constructability and maintainability (see Appendix D, Table D.3 for an extensive list of pros and cons). However, a disadvantage is its need for regular maintenance and degradation of components, which is even more relevant on high-speed lines [Ando and Aoki, 1999]; a special problem concerns imprints on the rails caused by ballast stones flying around. Ballast on concrete substructures is also likely to crush, causing premature degradation of the ballast bed [Russel, 1999]; additional measures, such as ballast mats, are therefore probably necessary.

\(^{51}\) At the time, the ETCS specifications were only just ready and operational systems not on the market.
Shinkansen slab track was another pre-selected system which was originally developed in the 1960s in Japan; this system was adopted for all locations on the new Shinkansen lines where the track system is supported by a concrete substructure [Ando and Aoki, 1999]. The Shinkansen slabs are 5 metres long and are anchored to the concrete substructure (anchors of reinforced concrete); below the slabs an elastic compound is used to reduce noise and improve the maintenance performance. It has proven to need little maintenance and to be well maintainable during night-time hours. On the other hand, construction costs are higher than for ballasted track and several other slab systems, though the introduction of ‘frame slabs’ may have reduced this disadvantage to some extent. The Shinkansen system can be considered a proven technology with known risks; vertical alignment can be corrected in the event of settlements through (costly) injections below the plates.

ERS has proven low maintenance needs and has several favourable properties compared to other slab track systems, in terms of required construction height, low dead weight, low maintenance needs and noise levels (see also Appendix D, Table D.3). It has been used since the 1970s in level crossings and bridges at speeds of 140 km/h and on two longer track sections (one with prefab slabs since 1976, and one with an in-situ slab since 1998).

Finally, the Rheda system was also pre-selected. The construction costs for Rheda, in which a concrete bed replaces the ballasted track, are relatively low, particularly compared to Shinkansen since the concrete bed is produced in-situ. Rheda should need little maintenance and renewal compared to ballasted track; settlements up to 26 mm can be corrected by re-adjusting the fastenings. However, the engineers expected a realistic risk that the concrete sleepers and supporting bed might crack, as hardly any elasticity was designed into the connection between the sleeper and supporting bed of the Rheda system, having been used for around 10 years at that time in Germany. Ultimately, these cracks and severe settlements may require reconstruction of certain track segments; in a worst-case-scenario this could take several weeks.

After EPC Track had identified the system properties as much as possible, a scorecard was composed during a joint session of all EPC working group partners in June 1999 (see Table 5.1). The ruling opinion was that ballasted track would be the best, particularly because it was a proven solution, easy to construct and inexpensive. The Shinkansen system also gained a high score. However, it was difficult to judge the impacts of aspects such as maintainability and maintenance needs through this qualitative approach; the scorecard also seemed rather subjective and did not relate these aspects to overall costs and performance levels.
Table 5.1: The developed scorecard of track systems

<table>
<thead>
<tr>
<th>Item</th>
<th>Weight</th>
<th>Ballasted track</th>
<th>Shinkansen slab track</th>
<th>Embedded rail on slab</th>
<th>Embedded rail in situ</th>
<th>Rheda</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity of settlement</td>
<td>1</td>
<td>5</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Height</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Dead weight</td>
<td>1</td>
<td>0</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Experience (proven solution)</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Noise and vibrations</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Connections to existing track</td>
<td>1</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Access to technology</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Capital costs</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Production time</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Daily maintenance</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Renewal</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Maintenance costs</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>82</strong></td>
<td><strong>71</strong></td>
<td><strong>44</strong></td>
<td><strong>45</strong></td>
<td><strong>56</strong></td>
<td></td>
</tr>
</tbody>
</table>

The management of EPC Track did not consider the scorecard approach to be satisfactory. Since the consortium ultimately had to deliver a fully priced, ‘optimal’ Performance Fee bid, the EPC Track group decided to approach the issue quantitatively by making clear assumptions and converting them into financial consequences for the different track structures. The minutes of the EPC Track meeting on 2 July stated: ‘It should be avoided that in September a choice for a particular track structure will be based on “intuition” and “a good feeling” due to time pressure. Moreover, the bankers require quantitative and transparent data’. During this meeting, the author was approached to propose (as soon as possible) a practical approach to identifying decisive cost drivers and risks in selecting the HSL track system, and to assist in comparing the alternatives. A work plan was prepared to: ‘Develop a model that can compare the costs of ownership, reliability and availability of the pre-selected track systems under the specific HSL South conditions, and use it to identify the most cost-effective and robust system’. Basic questions to be answered included: What are expected costs and performance of the different track solutions? How do the PPR, maintenance regime, interest rates and transport conditions influence the outcomes?

The analysis was performed in two stages. Firstly, expectations were generated on likely maintenance levels and failure times. Next, life-cycle cost estimates would be developed. Five persons were assigned to develop worksheets with downtime and cost expectations through a failure modes and effects analysis (FMEA), which allowed the degradation processes of the different track systems, the possible measures for prevention and monitoring, and the consequential impacts on costs and performance to be systematically identified. In the meantime, the author and an assistant elaborated the Life-Cycle Cost Plan (LCCP) system in order to include the particular HSL South conditions. Based on a first set of input data from the FMEA, the LCCP was then used to estimate a necessary Performance Fee for each track system.
The EPC Track management had agreed that the author would play an independent role, including an ex-post evaluation; however, management had also agreed to leave the first stage in the process of input generation as the responsibility of the FMEA team. This was not entirely according to the intentions, as stated in Section 4.4, but was considered unavoidable at that time, due to time pressure (with less than 3 months available) and the complexity of the task.

5.4 Assessing high-speed track designs – process and results

This section describes the course of the analysis project that started in early July and ended mid-September. After the first set of input data had been generated and the DSS had been modified during July (see Section 5.4.1), all staff involved worked together throughout August to validate the DSS models and to develop and discuss its input and output (Section 5.4.2). The results were documented and presented to the consortium in September (Section 5.4.3). The continuation of the decision-making process after this presentation is included in Section 5.4.4.

5.4.1 Modifying LifeCycleCostPlan

It was decided to develop a new computerised version of the LCCP from scratch. The models of the first DSS version were considered far too limited for the project. A number of modifications were made, the first of which concerned fitting all estimations to the required time periods. A distinction was made between the construction period (until 2005, as known at the time), the availability period (until 2029) and the guarantee period (until 2034). The IP was only expected to pay for major renewals during the last period (2029-2034). Secondly, details of the Reference Timetable, including the number of trainsets and the free nightly maintenance slots, were included (see Table 5.2). Figure 5.2 showed that high-speed trains can only operate at full speed along 65% of the entire route; Figure 5.6 (on the next page) shows the reason for this: accelerating takes a considerable amount of time.

Table 5.2: Summary of HSL South Reference Timetable, dated July 1999

<table>
<thead>
<tr>
<th>Until year</th>
<th>Maintenance hours (1 per 2 nights)</th>
<th>Average trains</th>
<th>Double track</th>
<th>Scheduled high-speed trains per hour per direction (TGV)</th>
<th>Scheduled local shuttles per hour per direction (ICs)</th>
<th>Period (construction during years 0-5)</th>
<th>Trains/day</th>
<th>TONNAGE</th>
<th>CUMULATIVE TONNAGE (incl. dynamic factor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>7</td>
<td>1,2</td>
<td>17</td>
<td>3</td>
<td>2</td>
<td>5-10</td>
<td>103</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>2014</td>
<td>7</td>
<td>1,2</td>
<td>17</td>
<td>3</td>
<td>2</td>
<td>10-15</td>
<td>103</td>
<td>95</td>
<td>190</td>
</tr>
<tr>
<td>2019</td>
<td>6</td>
<td>1,7</td>
<td>18</td>
<td>4</td>
<td>4</td>
<td>15-20</td>
<td>168</td>
<td>188</td>
<td>377</td>
</tr>
<tr>
<td>2024</td>
<td>4</td>
<td>2,0</td>
<td>20</td>
<td>4</td>
<td>6</td>
<td>20-25</td>
<td>220</td>
<td>256</td>
<td>633</td>
</tr>
<tr>
<td>2029</td>
<td>4</td>
<td>2,0</td>
<td>20</td>
<td>4</td>
<td>6</td>
<td>25-30</td>
<td>220</td>
<td>256</td>
<td>889</td>
</tr>
<tr>
<td>2034</td>
<td>4</td>
<td>2,0</td>
<td>20</td>
<td>4</td>
<td>6</td>
<td>30-35</td>
<td>220</td>
<td>256</td>
<td>1145</td>
</tr>
</tbody>
</table>

Thirdly, it was deemed important to develop a module that could indicate the possible consequences of choosing a particular track system in terms of performance penalties. There
was no prototype PSM available, which meant that a first, simple model was looked for that could indicate timetable adherence. The formulae, suggested in Section 4.3.5, were used despite their limitations. Knock-on impacts of delays on trains scheduled later could not be analysed very well in the event of long disruptions; in the case of a full blockage, all trains were therefore considered cancelled. In the case of temporary speed restrictions, all trains were delayed by an equal delay. Figure 5.7 shows the outcome of a delay calculation for a speed limitation over a short distance. It soon became clear that the indicated availability level could only be considered a rough indication. The approach taken had been agreed upon with the FMEA team; it was assumed that track failures would occur (on average) halfway through the operating day and the FMEA also made a distinction between maintenance and repair actions that could be performed within the free slots and those requiring more time. The penalty regime was also modelled, assuming annually flat availability levels.

Figure 5.6: Acceleration profile of TGV rolling stock

Figure 5.7: Impact of an incident on a single train
Passing time in this situation should be 271 seconds, and is 453 seconds instead.
Identical input tables and calculation models were used for each track system; interest rates, train delay penalties and a number of defined major risks in comparing the Performance Fees of the track systems could be easily switched on and off. Interest was included as an alternative-specific parameter, because lenders were expected to take more precautions and charge more interest for ‘unproven’ track systems.

5.4.2 Collecting and validating the maintenance expectations

The FMEA team, which consisted of five EPC Track engineers (excluding the author), delivered a first set of worksheets that became known in the consortium as ‘incident matrices’; they contained maintenance and failure expectancies, detailed according to different failure modes. The incident matrix for ballasted track was developed first, since its behaviour was presumed to be well known; incident matrices for the other systems were mainly constructed by reasoning on likely consequences of changed technical features (e.g. using data from suppliers and high-speed lines from abroad).

Each worksheet was based on a number of assumptions with regard to initial track quality and M&R, some of which were also input for LCCP. A key assumption was a maximum settlement of 50 mm for the substructure; although the Client had specified that it be ‘settlement-free’, the engineers saw a realistic risk of differential settlements of the substructure slabs, which was not covered by a risk-sharing regime. This was why the EPC Track group designed the Embedded Rails solution as a system of prefab slabs, although this was more expensive than construction in-situ with pavers. Another key assumption concerned the renewal thresholds for rails. This was assumed to be 700 million gross tons for ballast track with UIC60 rails on concrete pre-cast sleepers. Other assumptions focused on major preventative M&R, such as grinding. The data contained in the incident matrices could be summarised in figures on average preventive and corrective maintenance costs, possession and speed-restriction hours per ton carried or per year.

After this first set of rather detailed input data had become available, the FMEA team planned a couple of review sessions; the author was present during those sessions. Experts from outside the EPC Track group were invited, mostly in pairs, to review the incident matrices that had been developed and to propose changes. The incident matrices were reviewed in detail, which meant that all failure and small maintenance frequencies were discussed. First of all, this led to an overwhelming number of comments: each expert appeared to have his own ‘theories’ and experiences. They also had problems in translating their experience of a conventional network to a dedicated, still non-existing high-speed line. Discussions took far more time than expected, and one session easily took an entire morning. The incident matrices were modified are each session. However, there did not seem to be a ‘path of convergence’ in these modifications.

When the LCCP was ready for use during the first week of August, the author soon demonstrated that the entire impact of the discussed minor maintenance and track failures that were included in the FMEA would be in the order of only 10% of the overall Performance Fee. The construction costs, major M&R works, financing and a number of (separately defined) major risks appeared to have much more impact.
As a result it was decided to further focus efforts on these last factors and, in particular, the thresholds for major M&R and the likely cost and availability impacts. A set of M&R assumptions resulted, which both the FMEA team and the other EPC Track staff deemed realistic (see Table 5.3 for some key data). Some uncertainties remained, such as whether or not to include the renewal of a small percentage of the ‘sleeper population’. There seemed to be few sleeper problems on the Japanese lines. On the other hand, premature sleeper renewal seemed necessary in many European countries; causes were thought to be higher dynamic loads or inaccurate construction (e.g. quality of welds). It was decided to assume a small annual percentage of sleeper renewal.

<table>
<thead>
<tr>
<th>Table 5.3: Important data and assumptions (n.a. = not applicable)</th>
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<tr>
<td><strong>Height (mm)</strong></td>
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<tr>
<td>740-860</td>
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<tr>
<td><strong>Weight (kg/m)</strong></td>
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<td><strong>Vertical re-adjustability (mm)</strong></td>
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<td><strong>Fastening renewal</strong></td>
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<td><strong>Sleeper renewal</strong></td>
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<td><strong>Ballast renewal</strong></td>
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One remaining problem was how to cope with a number of special risks. First of all, the EPC staff considered ballast mats a necessity for a ballasted system on a concrete substructure. The rubber mats would dampen loads from the ballast bed and reduce friction between the ballast stones and the substructure in order to avoid any risk of premature track degradation. Including or excluding these mats made a considerable difference to the overall outcome (see Section 5.4.3). Risks that were included for the slab track systems were the correction of settlements, a small amount of rail renewal for ERS, and a repair of cracks in the Rheda system.

Although observations and issues had been passed on to other staff throughout the analysis, such as those preparing the consultation meetings with the Client, an official progress report was composed and presented on August 24 to the EPC Track management and a representative of the Steering Committee [Zoeteman, 1999c]. The following subsection discusses the outcome of this report.
5.4.3 Reporting the outcomes within the Consortium

The aim of the report was to present decisive design parameters and operating conditions and, most of all, to assess the cost-effectiveness of different track solutions. The following factors were found to be the most important: the interest rate, which influenced all cost areas; the construction costs, which determined the level of debt; the availability level of the system, due to the progressive penalty regime; the, due to the special risks involved; and the durability of the systems which determined in combination with the transport load and settlement expectancy whether component renewals would be necessary during the Availability or Guarantee Period.

The author reported the findings after a face validation session with experts. A set of 'illustrative', well-defined scenarios was used to answer EPC Track’s questions satisfactorily. Examples include:

- **Reference scenario**: as reflected in Table 5.3, with ballasted track without a mat, ballast renewal/cleaning at the end of the contract period and 6% interest;
- **Modified construction costs**: with a ballasted track design using ballast mats between ballast and concrete bed. The cost estimates of ERS and Shinkansen were also reduced by 10%;
- **Traffic load increase/decrease**: test concerning a 20% increase and decrease in the number of trains per hour over the entire availability period;
- **Strongly deteriorated availability levels**: test concerning the impact of a 2% or 3% lower annual availability during the entire contract period;
- **Increase of interest rates for slab track**: the effect of a higher interest rate for slab track systems was tested, since lenders will probably have more reservations. Interest is raised 1% point for Shinkansen and 2% points for Rheda and ERS;
- **Moderated penalty regime**: a similar, progressive penalty regime is used, but with penalty rates varying from only € 400 up to € 1500 per delay minute;
- **Moderated maintenance slot regime**: reducing the maintenance slots from 6 hours to 4 hours after the year 2015 is not applied;
- **Minor maintenance increase/decrease for slab track**: simulation using a 50% increase or decrease in costs and disruption due to minor maintenance and failures.

Ballasted track without ballast mats proved to result in 20% lower costs of ownership under the reference scenario (see Figure 5.8). Although the slab track systems perform much better in M&R, the identified risks had considerable cost impacts. For example, rail renewal for ERS would probably not be necessary within the contract period; however, if (partial) renewal were necessary, traffic disruption would be much more drastic for ERS; work methods that fitted into 4-hour slots were not yet available, due to the hardening time for Corkelast. Rheda was assessed as having high risks, particularly because of sleeper and concrete bed cracking (see Figure 5.8 on the next page). The ballasted track system proved to profit from the financing structure, i.e. a flat Performance Fee irrespective of the timing of expenditures; Figures 5.9 and 5.10 show the difference between the cash-flow patterns for ballasted track and for Shinkansen. With an interest of 0%, ballasted track without mats would have been 25% more expensive than slab track due to the planned amount of M&R. However, including interest worked out well, thanks to low construction costs and large
expenditures being deferred until the end of the contract. Revenues could be used to pay off loans in the first 20 years, resulting in a positive cash position. Contrarily, the slab track and ballasted track on mats solutions require high initial investment that does not provide the opportunity to pay off loans quickly and causes high financing costs.

![Diagram](image-url)

**Figure 5.8: Annual Performance Fee required for the reference scenario (MIO EURO)**

![Diagram](image-url)

**Figure 5.9: Cash flow for ballasted track for reference scenario (no mats)**
A further insight was obtained by comparing the reference scenario and the scenario with modified construction costs (see Figure 5.11). Including ballast mats and reducing the unit costs of Shinkansen and ERS by 10% entirely changes the outcomes; ballasted track then became the most expensive system. The increase in construction costs (by € 400 per metre) for ballasted track, estimated by EPC Track, resulting in a toppling of the outcomes. Ballasted track was now as expensive to install as the other track systems, while still more maintenance was expected.

Figure 5.11: Annual Performance Fee required using modified construction costs (MIO EURO)
Analysis of the various scenarios resulted in several more insights, the most important of which was the huge impact that the PPR could have with regard to the necessary Performance Fee. Section 5.2 may have indicated this to some extent, but the impact had not yet been revealed at the time of the Consultation Phase. Figure 5.4 already showed that, theoretically, 90% availability throughout an entire year would result in penalties of € 213 million. Naturally this would result in bankruptcy and termination of the contract, which is why this availability range should be avoided at all times. However, the analysis also showed that availability levels of 97-98% already lead to significant penalty levels, which is why system availability had to become a key issue in the design process. Figure 5.12 shows the Performance Fees based on the assumption that other subsystems, such as signalling and power supply, would already ‘consume’ 2% of annual unavailability. It shows that the costs of train delay penalties are now, more or less, the same size as the direct costs of construction and M&R. The negative impact is larger for those track systems that already have a lower availability; note that this figure is based on the reference scenario (no ballast mat).

![Figure 5.12: Annual Performance Fee required with 2% more unavailability (MIO EURO)](image)

A drawback of the study was that it could not select an undisputed winner among the solutions. The differences in the overall outcomes for slab and ballasted track on mats were small. Although Embedded Rails and Rheda would not need large budgets for inevitable M&R work, costly risks were considered possible. These risks were, at least at that time, hard to quantify and it was not expected that Monte Carlo simulation could help in this situation. However, progress was expected on this issue, if agreement could be reached with the State on a number of risk-sharing principles. Finally, the report recommended speeding up the development of a prototype performance simulation model. Considering the impact of the PPR, the estimation of availability with the model implemented in LCCP was considered too simplistic, as it did not take account on various complexities.
5.4.4 The decision-making continued: the internal process

During the meeting of August 24, the EPC Track management concluded that the overall performance of the different track structures was probably within a smaller range than that suggested by the qualitative assessment in July. Management also concluded that Rheda scored rather well and was the preferable solution in the event that differential settlements could be limited to less than 25 mm. If this could not be guaranteed, then Shinkansen slab track would probably be the best choice.

The management team expected that decision support with the help of LCCP would be necessary for the coming 2 months in order to include the consequences of more accurate inputs. They also foresaw that the risk margins to be included required more discussion within the consortium. After the meeting, the progress report was distributed to the other stakeholders in the consortium.

A major change in the decision-making process occurred after a special symposium on ballastless track on September 9; the Dutch State had organised this symposium for invited staff of the four consortia. The impression of that day was that the requirement to limit track construction height to 360 mm would be maintained as an absolute requirement, ‘possibly politically determined’, as expressed during the EPC Track meeting of September 15. The State emphasised that it favoured Embedded Rails and Direct Fastening (DF) as a second-best option [see HSL PO, 1999d].

DF was not a solution that had been pre-selected by the consortium, but after this symposium it became one of the favourable options. In DF, the rails are mounted onto baseplates that are attached directly to the concrete deck by two or four anchor bolts. An elastic pad is placed between the baseplate and the concrete deck. The principle reasons for not including DF earlier had been: (a) the expectation of labour-intensive maintenance work, due to the dynamic loads on the fastenings and (b) the absence of an ‘industrialised’ construction process. During the symposium, representatives of the State mentioned that progress could be expected on this last issue [HSL PO, 1999d], and that the construction of an adequate ‘interface system’ between substructure and track system was open to discussion. This interface system would dampen differential settlements in the substructure. The consortium chose to design the DF system such that the concrete supporting bed could be constructed in-situ using a paver. The anchor bolts could be drilled afterwards into the concrete structure and glued to the holes.

Once a DF design had quickly been developed, the EPC Track management asked the FMEA team and this author to develop a new assessment of the expected Performance Fees for all track systems. New estimates were needed within 1-2 weeks, which prohibited any validation efforts. The DF design was estimated to be slightly more expensive than Rheda. The DF design could score fairly well, mainly because costly availability risks were not expected; corrections to the geometry were possible, thanks to the re-adjustability of the fastenings, and this M&R would fit into the free maintenance slots. The results were presented to a small EPC Track committee on September 15 and were ‘recognised’ to some extent. However, there was a general feeling that more research would be needed into both construction estimates and maintenance needs of the DF design in relation to the high-speed environment of the HSL (impact of vibrations). Nevertheless, just before the Tendering Phase
commenced, the Steering Committee had already decided to start developing a Base Tender using DF and an Alternative Tender based on Embedded Rails.

In October, an error was found in an input parameter for LCCP, which meant that risk and penalty margins on top of the Performance Fees for all track systems had been too low, based on the assumptions made in August. Journey time on the conventional tracks near Rotterdam had been accidentally included in the journey time calculation. Because the risk assumptions were already considered too high or irrelevant, after the aforementioned symposium, the effect of this error was considered minor. No further analysis was undertaken.

In November, more information on the Client’s policy became available as part of the Consultation Phase Protocol that, apart from the internal decision-making process, described the official response of the State to the issues raised during meetings. This is further discussed in the next subsection.

5.4.5 The decision-making continued: the Client’s policy

The Consultation Phase Protocol, together with the Invitation to Tender (ITT) documents, defined the degrees of freedom for the consortium’s bid. The most remarkable change, as stated in the Protocol, was the relaxation of the construction height criterion, enabling the tenderers to submit a broader range of track designs [HSL PO, 1999e]: a track construction height up to 480 mm would be acceptable for the Base Tender. The consortium could propose modifications to the height of civil works, such as viaducts and substructure, in an Alternative Tender, although the design height of 5.30 metres for the catenary had to be maintained.

Another change concerned a relaxation in the regime of maintenance slots for major M&R works. A regime for planned major renewals was now put forward, which allowed the IP to purchase extra possessions at a low price, as long as they were announced 6 months prior to execution. The State also showed more willingness to share in risks relating to the substructure. The Protocol stated: ‘An Alternative Tender that is based on the State as insurer of last resort for latent defects risks related to the Civil Works (e.g. settlement) beyond year 10 will be acceptable’.

Further information was also obtained in relation to acceptable Performance Fee structures. The State allowed tenders to propose an Alternative Tender with a ‘Performance Fee that would (partially) depend on actual usage of the railway infrastructure. However, the State is likely to look more favourably on a regime that: a) provides significant benefits, b) is robust and unambiguous over a 25-year period and c) includes a Performance Fee that varies with traffic, both upwards and downwards’.

The algorithm to attribute train delay penalties to the Infrastructure Provider had been slightly modified in order to cut off the penalty impacts of failures, leading to long obstructions (see Figure 5.13). It would avoid extra delay (other than the scheduled journey time for that day) being attributed to the IP. Other suggestions by the consortium, such as a time-related availability calculation, with penalties based on actual delay times, were not acceptable; they would possibly change the starting points of the PPR too much.
5.5 Optimising designed system performance – aims and approach

The Tendering Phase took place in the winter of 1999/2000; the *Invitation to Tender* was received officially during the first week of December after a period of apparent delay. In the meantime, some activities had been implemented within the consortium. For example, the technical disciplines – track, power supply and signalling – had continued engineering the HSL’s design; the choice for a Base Tender with Direct Fastening and an Alternative Tender with Embedded Rails had not been revised.

In order to arrive at fully priced tenders by the end of February 2000, a process for supplying these ‘Performance Fee ingredients’ had been devised. The following costs needed to be estimated:

- engineering, procurement and construction (EPC costs);
- maintenance and renewals (M&R costs);
- requested possessions during off-peak hours (Possession Costs);
- condition and train-delay penalties, including non-available days (NADs); and
- financing, determined by the interest rates charged by lenders and the required funding by the partners themselves (also referred to as ‘equity’).

Train-delay penalties would require special attention throughout the entire estimation. The following roadmap for the bid preparation was envisioned in the consortium:

1. *Estimating failure time and frequencies (using constant failure rates, related to traffic intensity).*

   It was decided to develop so-called ‘incident matrices’ that had to contain some level of detail for all possible failure types, their estimated frequency of occurrence over a 25-year period and the mean time to restore services (MTTRS). These incident matrices had to be developed by each technical discipline for their own subsystem in a collaboration between M&R-Co and EPC. The engineers were asked to estimate minimum, maximum and probable frequencies of each failure type. This approach would result in a comprehensive ‘risk register’.
2. **Forecasting availability levels**
   Next, the impact on the availability of the overall system could be estimated using a prototype performance simulation model (PSM). Monte Carlo simulation would specify availability levels for different confidence levels.

3. **Calculating the Performance Fee**
   Once the availability levels were known, the train-delay penalties could be determined and added to the costs of design, construction, maintenance and renewal. All cost data was then entered into the Financial Model, to be further developed by the participating banks. The model included variables such as tax and interest and would result in a Performance Fee.

   The aforementioned steps could only be fully performed once all data and models were ready, at the end of the Tendering Phase; however, in order to improve the design and M&R plans, it was deemed important to have (during the design process) an insight into the contribution that the subsystem designs made to the overall Performance Fee. Since the Client had stated that the net present value of this Performance Fee and its robustness was considered the most important criterion [HSL PO, 1999c, Clause 3.7.8], assessing the various design and M&R solutions on their overall cost impact should ensure that the consortium submitted a competitive bid.

   A small committee consisting of members of the Steering Committee and the Financial Working Group (including this author) signalled during its meeting on December 9 that the design work within the consortium did not seemed focused on realising a certain, optimal performance level. The EPC teams worked independently on their design solutions without taking account of system availability; communications between EPC and M&R-Co did not seem to be fruitful. This might have been caused by the fact that many new people had become involved in the project and that priority was given to developing an initial design. Incident matrices had not received much attention and a ‘picture’ of the overall performance was completely absent.

   The Steering Committee therefore asked the members of the small committee to quickly set up a process for analysing the current net present value and robustness of the consortium’s bid and to trigger improvements in the design and maintenance plans that could reduce the net present value of the consortium’s bid. For example, the consortium management wanted to know whether it would be better to allocate additional budget to, for example, signalling rather than to track (or vice versa).

   With regard to the investment of the subsystem design, a pattern of increasing and diminishing returns on investment was expected (see Figure 5.14). On the one hand, the consortium’s revenue would increase with each percent more availability, thanks to fewer penalties and NADs being attributed. The higher the availability, the smaller the marginal reduction in penalty rates, owing to the characteristics of the PPR (see Section 5.2). On the other hand, the required EPC and M&R costs were expected to grow disproportionately after a certain design quality, since increasingly costly measures (such as redundant systems and top-quality materials) would be necessary. Somewhere, there should be an optimum level of availability; however, during the Consultation Phase it had become clear that it would be necessary to aim for a rather high availability, possibly in the order of 99%. An approach was
needed that could answer the following question: ‘What are the different design and maintenance options, how do they affect the duration and frequency of the incidents and planned possessions, and what is the effect on the required Performance Fee?’

![Graph showing additional revenue for 1% increase versus additional investment for 1% increase.](image)

Figure 5.14: Presumed law of increasing and diminishing returns on investment

The incident matrices were considered the key to success: they should reveal the contribution of different failure types to the direct EPC and M&R costs as well as non-availability. Figure 5.15 on the next page shows the required estimation steps for the LCC estimation (for the first 30 years), in which LifeCycleCostPlan would be necessary to estimate penalty levels and overall life-cycle cost distributions between the subsystems. Each subsystem’s design and M&R plan results in direct costs (construction, M&R and track possessions) as well as expected failure frequencies and restore times. The costs of train-delay penalties and the direct costs of EPC and M&R together comprise the overall life-cycle costs and, hence, the Performance Fee required.

A question to be resolved was how to develop an approach that could provide a reasonable estimate of the Performance Fee in about 2 days. A shortcut would be needed as the aforementioned roadmap would take too long and required models that were not yet available. The committee expected that the following approach, with LCCP as the cornerstone, would work out well.

1. All disciplines were asked to fit the diversity of failure types in the incident matrices into a limited set of ‘incident profiles’, which defined standard full blockage and speed restriction times (see Figure 5.16 for examples).
2. A preliminary prototype PSM, provided by one of the consortium partners, would estimate the average amount of delay time for each incident profile. The resulting ‘catalogue’ of delay times and non-available days could be used in the LCCP. A new run by the PSM would only be necessary if a new incident profile was added or an existing profile modified during the process.
3. LCCP would estimate costs of penalties and NADs and combine these with the direct costs of EPC and M&R in a life-cycle cost analysis. LCCP should be able to present the individual contribution of each subsystem (track, power supply and signalling) and even each incident profile.
This author was asked to develop the LCCP, together with an assistant, while two other staff would organise the participation of the engineering teams. Section 5.6 describes the course of this process, which was ambitiously introduced in the consortium as ‘the optimisation process’. The prototype PSM, which estimated train delays per incident profile, was developed and managed elsewhere in the consortium.

5.6 Optimising designed system performance – process and results

This section describes the course of the study, which started in December and was finalised at the end of February; this date was only possible because the Client postponed the submission
date for the tenders to the end of March after adding new engineering work to the contract in January (concerning mechanical and electrical equipment). Similar to the first case study, the process and results of this study are discussed below in a number of subsections.

5.6.1 Modifying LifecycleCostPlan

The LCCP was redesigned to provide a simple and easily presentable attribution of direct costs and penalties to the responsible subsystems for two alternative rail system designs, one based on Direct Fastening track and one using Embedded Rails.

The main change concerned the requirement to attribute penalties to individual incident profiles for all subsystems in the HSL railway infrastructure; however, only around two weeks of modification was needed. The PPR was already included, while the module for estimating availability had become superfluous, as it was replaced by the aforementioned catalogue of incident profiles. Further, the estimated costs for EPC and M&R over the years, provided by the engineering teams, were included; costs for incident response were included in the annual maintenance costs for each subsystem. The progressive penalty rates made it necessary to first estimate the overall penalty level per year for the system, before allocating this to the different incident profiles, according to their relative contribution. This procedure was not required for the NADs, as the financial staff had estimated a monetary value per NAD; this could be used as a fixed value, to be updated from time to time.

Some key performance indicators were summarised in a graphical so-called ‘Incident Analysis’ interface; this computer screen indicated immediately changes in penalty costs as a result of proposed design or maintenance measures. The screen shows how many euro are available for further investment, for each minute of delay reduction.

Although the described approach was already expected to result in a much better estimation of system availability and corresponding penalty amounts than the previous LCCP version, the outcome still had a number of limitations. The first was that the LCCP was based on a flat distribution of delay minutes within a single year, while performance would be measured on a monthly basis. However, a more refined approach was not considered possible; the possible consequences were discussed in the small committee and were considered acceptable. This approach usually results in an underestimation of real penalty levels, due to the progressive penalty regime. This meant that the calculated penalty savings would indicate the minimal, justifiable amounts of investment in improved designs and maintenance strategies. A further limitation was that LCCP distributed the failures, and hence the penalties and NADs involved, equally over the 25 years of the Availability Period in order to calculate the net present value of the Performance Fee. This was probably not an adequate representation of reality, where failures would occur more during certain life-cycle phases of the rail system. An effort to resolve this issue is briefly discussed at the end of Section 5.6.2.

5.6.2 The ‘optimisation process’

A first ‘Optimisation Workshop’ took place on December 22, 1999, which was 3 weeks after the initiative to organise the process had been taken. In the meantime, the modifications to the LCCP had been performed and a first set of input data had been derived from the submitted
incident matrices, using the prototype PSM and the LCCP. As the PSM had been developed and managed by another section of the consortium, the process leaders, including the author, received only output data. The PSM was in fact a queuing model of the train operations on each HSL track and included all relevant data, such as the reference timetable and parameters expressing the relative importance of particular train services.

The first workshop, in which each technical discipline (Track – T, Power Supply – P, and Signalling – S) was represented by two representatives (from EPC and M&R-Co), was ended after 2 hours; apart from a promising response from the Signalling group, requested tasks had not been performed properly. Some participants had accidentally taken outdated versions of the incident matrices with them, while others had wrongly allocated the failure types to the incident profiles. The output from the preliminary PSM also proved to be incorrect because the dampening factor for long delays (see Figure 5.13) had not been included. The conclusion of the workshop, as specified in the minutes, was that: ‘We still don’t have a forecast of the system availability and the contribution of the disciplines to this availability’.

The second workshop was scheduled for the first week of January 2000, directly after the Christmas break; in the meantime the participants were expected to considerably improve their contributions. It was made clear that a high availability must be achieved, while also reducing EPC and M&R costs, in order to achieve a competitive bid. It seemed that the ‘designed availability’ was too low, while EPC and M&R costs were high compared to the Client’s expectations. A set of review questions had been formulated to assist engineers when revising the incident matrices. Those questions were:

- Can the (cost-driving) failure be eliminated?
- Is the mean time between failure (MTBF) correct? Is it time-related or load-related?
- Can the number of objects (components/assets) subject to the failure be reduced?
- Can condition-based or calendar-based M&R avoid the failure?
- Can the predictability of the MTBF be improved?
- Is the estimate of the mean time to restore services (MTTRS) correct?
- Can the time be reduced, i.e. to respond, take the track out of service, collect spare parts, repair the damaged components and clear the site?
- Can the post-failure or post-maintenance speed limitation be raised?
- What is the effect of applying a temporary repair solution?
- What is the influence of the signalling block length?
- What is the effect of cost reductions on the number of failures?

The engineers were assured that new design and M&R solutions that may ‘emerge’ from the workshops would not be directly imposed as a design rule for their team; but they should consider proposed measures seriously. It was hoped that this would help them to ‘think along’ during the workshops. The aims of the optimisation process were now formulated as follows:

- to balance EPC and M&R costs with penalties;
- to allocate penalties to the disciplines responsible;
- to check the reasonableness of frequencies and repair times of incidents; and
- to approach the ‘optimisation’ of the rail system in an objective way.
The process leaders found the second workshop to be more successful. All participants had delivered updated incident matrices in advance, and this provided tangible evidence that most of the disciplines had made serious efforts to improve them. This allowed an initial estimation of costs and minimal penalty levels. However, a drawback that came to light during the workshop, was that the engineering teams did not seem to have reviewed and updated their design and M&R plan in relation to each other. The failure estimates contained in the incident matrices had been improved, but most representatives failed in explaining how these changes had come about, through changes in the design or M&R plans. Apparently, they had not been well informed by team members.

Although a complete and consistent set of data was available, it was nevertheless decided to compose a progress report with a number of preliminary conclusions [Zoeteman, 2000b]. The report, which included all data used, was distributed to all stakeholders in the consortium and contained two main conclusions. Firstly, the costs of construction were high. Secondly, the availability estimation had resulted in a remarkable outcome. On the one hand, the estimated availability level of around 98.5% (for both the Direct Fastening and Embedded Rails variant) was considered fairly acceptable. However, on the other hand, hundreds of NADs were expected. This unexpected outcome was caused by the fact that most failures leading to full blockage seemed to result in an NAD. It was concluded that all design, maintenance, and repair measures should aim to ‘keep them [the trains] running’; this meant that strategies should minimise blockage time at all times.

During the week following distribution of this report, on January 10 to be precise, a third workshop was organised, which was dominated by a dramatic deterioration in the outcomes. The initial aim of the workshop (to brainstorm on possible EPC and M&R cost savings) was abandoned, after having processed the updated data submitted by the engineers. The main cause for the significantly lower availability forecast, in the order of 97%, was a modified expectation on the number of failures for high-speed crossover switches. Apparently, EPC Track had so far underestimated this risk for the reliability of the infrastructure.

The minutes of the meeting stated that it was worrying that the disciplines seemed to change the incident matrices each time and that the design and incident matrices were not reviewed integrally. It would be useless to look for any direction for improvements when the input data remained volatile and unreliable. The issue was also on the agenda of the Financial Working Group meeting held on January 13. It was decided that stabilisation of the failure expectations and the supply of ‘real proof’, e.g. from the French TGV network, had to become top priority. The situation within the consortium regarding incident data was considered unacceptable, also because a project information document had to be delivered to potential lenders in February, which should underpin the expected funding required for the project. An obstacle signalled during the optimisation process so far was that too many people were participating in the workshops. The various disciplines also did not send staff members who were authorised to make clear commitments. From now on, all senior engineers and EPC managers were expected to participate. A presentation was also given to members of the Steering Committee; they asked the group to focus on the failure distribution over time for the development of a life-cycle or usage-based Performance Fee.
In the fourth workshop, held on January 25, this approach was successful. The managers of the engineering teams attended the workshop and the project leaders underlined the urgency by introducing the new request by the Steering Committee. Several new design and maintenance options were discussed during this workshop.

Two more Optimisation Workshops were held (February 9 and 15) during which, finally, design, maintenance and incident response alternatives were seriously proposed and analysed. It seemed that the disciplines could argue reasonably well on the failure levels included in their incident matrices. The data had also more or less stabilised. Surprisingly, the consortium had taken new interest in a Ballasted Track variant for an Alternative Tender. This decision may have been due to the high cost estimates for Direct Fastening and Embedded Rails.

5.6.3 Reporting the outcomes within the consortium

At the last workshop agreement was reached on a set of data that would be used for a final report on the optimisation process [Zoeteman, 2000c]. The author composed the final report, which was distributed on February 18. The set of data resulted in an average annual availability level that was again in the order of 98%. Figure 5.17 on the next page shows the illustrative cost breakdown, as contained in the report. Apart from the high-speed switches, a significant performance improvement had been achieved. The report listed a number of measures that had emerged directly from the Optimisation Workshops. For example, a special response scenario had been elaborated for the switches connecting the HSL to the conventional network near the town of Breda. A bi-directional traffic regime (on a single track) could be applied in the event of failures, thanks to the planned installation of a pair of crossings nearby. Another example concerns the use of mobile flash-butt welding machines for rail repairs. Final examples are condition monitoring and redundancy in control systems.

Despite these measures, the overall outcome of the final report had not changed dramatically compared to the report in January and, for the Base Tender, not in a desirable direction. Several renewals had been eliminated and higher speed limits for the remaining renewals were considered possible. However, EPC costs had hardly changed, whereas the costs for maintenance and non-availability had increased. The question of how this increase in annual maintenance costs was related to the changes agreed at the Optimisation Workshops could not be answered, because the engineering teams had never presented the details of their design and maintenance plans. The process leaders had not made that an issue, as all efforts were focused at the time on improving the quality of the incident matrices. Possibly the maintenance costs had not been estimated accurately in January. During the last two workshops, an effort had also been made in detailing the failure patterns over time. The LCCP had been quickly modified to allow the impact of these failure patterns to be studied. Although the participants had perceptions of the impacts of the degradation processes, it was considered impossible to make well-grounded forecasts that could be used for fine-tuning the Performance Fee bid in this way.
5.6.4 The decision-making continued

The bid was further prepared according to the roadmap described at the start of Section 5.5; system availability was forecasted using the prototype PSM under the assumption that failures would occur randomly over the years. Remarkable changes still occurred in the design and M&R plans, as well as the incident matrices, after the Optimisation Process had ended. Firstly, Ballasted Track had finally replaced Embedded Rails for the Alternative Tender; it had gradually 're-entered' the arena, possibly as a result of pressures from potential lenders and other partners. The aforementioned report by the author, already included a Ballasted Track variant in an appendix. Secondly, the Steering Committee had commissioned an Audit Team to review the design and maintenance plans. As a result, all technical groups had to make changes to their incident matrices in March 2000, and this meant that a couple of changes proposed by these groups during the optimisation process, had to be revised. The Audit Team also urged a benchmarking exercise between the consortium’s bid and the situation on the Belgian HSL (Brussels-Lille). Although the situation was rather different – the Belgian HSL had, for instance, two maintenance slots per day available with 8 hours at night – it urged the engineers to modify their estimates, particularly for the high-speed switches. A distinction was made between regularly and incidentally used switches. In the end, a bid was offered to the Dutch State with an annual availability level of 99%.

In July 2000 the three participating consortia received an Invitation to Modify (ITM), as a number of conditions had changed and the State wanted to receive bids offering more value for money. The group only had around 6 weeks to develop a modified bid. The State had decided to change certain conditions, some of which had, remarkably, already been the subject of discussion during the Consultation Phase. The maintenance slots were extended from 4 hours to 6 hours and several other conditions for assigning penalties were made less strict. However, the most remarkable change was a drastic cut in the expected number of trains on the HSL. The ITM gave the maximum number of trains per hour (TPH) per direction...
as 6, instead of 10 from 2015 onwards; only four TPH were expected during the first 15 years. This change would probably have significant impacts on the amounts of M&R and failures to be expected (minutes of meeting, July 5). For example, practically all track renewals could be left out of the equation, as the cumulative tonnage was effectively halved.

Once this was decided, one of the Optimisation project leaders asked the author whether decision support could be provided for modifying the design plans in relation to the new conditions. However, a straightforward approach would be required, as there were only a couple of weeks available. The author therefore developed a modified LCCP that resulted in a simple MS Excel worksheet (approximately an A4 page), which was named the \textit{LCC Easy Estimator}. This remarkable reduction in complexity was based on insights from the Optimisation Process, which had shown that a distinction between \textit{major} and \textit{minor} incidents was possibly based on the delay caused. The assumption was made that the minor incidents would not result in an availability level below 99\% during one of the 13 yearly performance periods, while not more than 1 major incident (causing NADs) would occur in a single performance period. With this assumption, it was possible to estimate the penalty costs on a monthly basis, while their validity could be checked on the worksheet, because the annual availability had to be over 99\%.

The tool was available within a couple of days. However, in the meantime, the Steering Committee had decided to approach the Modification Process in a pragmatic way; simple cuts in costs had to be identified. Possibly, they feared a (sort of) repetition of the Optimisation Process, which would take too much time and change too many parameters in the Performance Fee. Drastic design changes were no longer considered an option, except for the power supply and crossover switches. The people leading the Optimisation Process were allowed to study the contribution of crossover switches to penalty reductions, now that traffic intensity would be lower. The PSM used by the consortium proved not suitable for including the use of crossover switches. The Systems Engineering department (Faculty of TPM, TU Delft) was therefore asked to advise on the usability of crossover switches on the HSL. They developed a simulation model of the HSL system, which was able to estimate delay times caused for the various incident Profiles, with or without these switches. Despite much progress being made, also this study had to be stopped after a couple of weeks due to lack of time; usable results would have come too late to be included in the consortium’s bid.

New opportunities for LCC-based or other analytic support would not occur after August 2000. Two competing consortia received an \textit{Invitation to Negotiate} and they submitted a ‘Best and Final Offer’ in March 2001. \textit{Infraspeed} was eventually awarded the IP contract in October 2001, which was the largest contract ever awarded by the Dutch government to a private company. Infraspeed had arranged € 1.2 billion of initial funding and offered a Performance Fee for an ‘availability level' of 99\%, which should amount to approximately € 2.7 billion over the entire period [Zoeteman and De Weij, 2003]. Rheda2000, a redesign of the Rheda system, is used as a basis for the track design.

This chapter showed that the consortium struggled to select a track system within the context of the HSL project. Section 5.7 briefly puts the consortium’s efforts into perspective by referring to other studies in the field. Chapter 6 continues with the third case study.
5.7 Reflection: the HSL track selection put into perspective

One of the problems experienced by the consortium concerned the fact that the new track systems might outperform existing technology within the first 30 years after installation, in terms of reliability and costs, but that events were considered possible which could threaten system performance significantly. Figure 5.18 depicts this dilemma: System A may be Embedded Rails, while System B may be ballasted track on mats. Life-cycle costs of System A are probably lower, but uncertainty margins are much larger, which is made worse by the regime of heavy, progressive penalties. People in the consortium were confused about the ‘product’ expected by the Client. On the one hand, the consortium was asked to deliver the lowest Performance Fee for maximum availability (including full responsibility for all possible risks) while, on the other hand, proven technology had to be offered. These risks were continuously subject to debate, as realistic budget reservations for risks had to be included in the bid, and this surely put so-called ‘unproven’ track systems at a disadvantage.

![Figure 5.18: Uncertainty reflected in probability density curves (total area under each curve is 1. Track System A represents an ‘unproven’ track system)](image)

Interestingly, there are clear indications that on the Client’s side people had also struggled with the track selection issue during the HSL tender, already years in advance. This becomes clear when analysing some visible events by the Dutch State in relation to the track system design. Several publications show convincingly that there was an active search for feasible track systems for the HSL. During the Consultation Phase, the Client favoured ERS or a Direct Fastening system, but this did not seem to have been consistent over time. In 1997, the State sent a letter to the Belgian railways stating: ‘The HSL Project Organisation refrains from an integral introduction of Embedded Rails as the track system. This implies that we also refrain from a possible test at the NMBS on your network’. The letter was probably sent at a point where the development of a ‘settlement-free substructure’ had not yet been envisioned; the bad quality of the subsoil was mentioned as one of the reasons. According to the letter, a Direct Fastening system would be developed. Despite the cancellation of the field test, the letter stated that research on ERS would continue with the assistance of computer models of track behaviour [see Schooleman, 1999].
A remarkable event (in 1998) was the construction of a 3-km test bed of ERS, built by ProRail/RIB using a slipform paver near the village of Best. After construction, it was tested at speeds of 140 km/h. The construction costs proved to be high, but not excessive. Several parties involved in the test performed studies that indicated that the construction costs were low enough to result in a reduction of total life-cycle costs, compared to ballasted track. The author performed a quick-scan for Strukton Railinfra using the prototype LCCP, which indicated that a life-cycle cost reduction of 20% was possible over a period of 45 years; cost implications of earthworks and settlement risks had been left out of the preliminary analysis [Zoeteman, 1999b]. After this ‘Best pilot’, a potential high-speed test at the test centre of the Association of American Railways in Pueblo, Colorado, was cancelled, probably due to operational or budget problems.

Another study, performed by Esveld and Rolf [1999] for the HSL Project Organisation, proved to have a similar outcome; the study was based on interviews with track experts and ProRail/RIB data. This study was set up to estimate possible life-cycle-cost levels, for a period of 90 years, of a ballasted track on mats, Shinkansen, Rheda and ERS with a paver on a settlement-free substructure. Lower, middle, and upper estimates had been made for each system based on a number of scenarios, in order to assess the robustness of the outcomes. ERS resulted in the lowest life-cycle costs, although the lower estimates for Rheda and Shinkansen were lower than the upper estimate for ERS (prefab construction). The range of the expert judgements used for the construction cost estimate for Rheda and Shinkansen was still relatively large and the ranking could therefore change under certain conditions. However, ballasted track was always more costly than ERS. The conditions of the developed IP contract, i.e. the time period of 30 years, the private funding requirement and the PPR, were not known or relevant.

All in all, it seems that differences in the outcomes of the various studies can be directly explained by a number of different starting points that reflect contractual conditions (time horizons, interest rates etc.) and risk perceptions. The results of the study of Esveld and Rolf were apparently still used by the State in the symposium on ballastless track of September 9, 1999 [HSL PO, 1999d].
6. Case 3: Track Renewal Policy

This chapter discusses the third case study, which concerned a review and revision of ruling principles in the planning of track and switch renewals on the Dutch network. The case study, known as the Life Cycle Management Plus (LCM+) project, was performed in 2000 and 2001 within the Railinfrabeheer (RIB) organisation, now part of ProRail. The company will continue to be referred to here as “ProRail” for reasons of simplicity. Section 6.1 introduces the context of the LCM+ project. Section 6.2 goes on to explain its aims and work approach. Sections 6.3 to 6.5 describe the subsequent phases in the analysis process. Section 6.6 discusses the implementation of the LCM+ findings in 2002. Finally, Section 6.7 briefly presents the latest developments in track renewal planning. Note that the evaluation of this case study is included in Chapter 7.


This section provides a brief overview of the case study context, the planning process for track and switch renewals; this management area was considered well suited for a final test of the LCC-based approach. Firstly, track M&R proves to be the most costly element in the preservation budget. Railway tracks, switches and level crossings consumed 50% of the maintenance costs and 70% of the renewal costs in the Netherlands between 1995 and 1999 [Swier and Zoeteman, 2000]; Box 6.1 on the next page discusses the financing of the track M&R in more detail, which is important to understand later observations. Secondly, tracks and switches contribute significantly to the disruption of traffic. Track M&R needs long planned possessions, but suffers few failures; it is mainly replaced for reasons of railway safety, riding comfort, increasing maintenance needs etc. Switches are, however, also important sources of failure [Duimmeijer, 2003]. Thirdly, (more) condition-based strategies seemed feasible for tracks and switches, as degradation can be timely observed.

The daily work within the Preservation Division of ProRail is briefly discussed first, in order to better understand the setting of this case study. The division distinguishes three different work processes in maintaining the infrastructure, each having separate budgets:

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52 Appendix E discusses how track maintenance and renewal policy was substantiated and managed in the NS up to the 1990s; it is intended for the interested reader.

53 Facets of the ProRail organisation were also mentioned in Sections 2.2.1 (Life-Cycle Management, Output Process Contracts, financing in the 1990s) and 2.3.1 (Internal Organisation).
1. **Inspection, minor maintenance and incident repair:** this type of work is outsourced to contractors in so-called Output Process Contracts (OPCs). Where possible, these contracts are based on performance-based specifications, such as incident response times and track quality. The contracts are generally issued for periods of 5 years, while the exact fee for the contractor is settled per year.

2. **Major maintenance:** this type of work can be tendered or is performed by the area contractor under a special project code.

3. **Renewals:** ProRail organises the large-scale replacement of assets that have become too degraded for rehabilitation, through public tenders. Renewal plans are generally based on a variety of information, such as theoretical stand times, reports from the contractors, failure reports, additional inspections and expert judgements. They are also included in the production plan.

Box 6.1: The financing of Track Renewal put into perspective
[Information supplied by ProRail/RIB B&I Control, G. Joosten]

ProRail owns the railway infrastructure economically; however, only part of the infrastructural assets is properly included in the balance sheet. This is a result of historical factors. The railway network as it is, has been constructed with the use of government funding (fond-perdu or cash funding), funding by third parties (e.g. municipalities), and a loan facility for ProRail. Part of the assets has been depreciated entirely and is not visible at all in the balance sheet. Further, much construction and renewal work on the network, mainly being Track Renewal, is directly settled as operating costs in the particular year. Track Renewal has a special position, because it is treated as a regular expenditure and not as an investment. For many other assets (in other technical subsystems such as Signalling and Power Supply), depreciation is used, based on historical acquisition prices. Often this depreciation method results in insufficient budget for the 1:1 replacement of these assets, given the long lifespan of rail infrastructure (often several decades). Moreover, this budget is also used to replace assets which were originally financed with cash funding (fond-perdu).

The property included in the balance sheet is thus a poor representation of the infrastructure found ‘outside’. It implies that annual negotiations between ProRail and the Ministry of Transport are required for Track Renewal, whereas the other disciplines such as Signalling and Power Supply are in principle financed through (insufficient) depreciation. Because it is expected that major replacements are also needed in the coming decade(s) for Signalling and Power Supply, ProRail is currently developing a first-ever multi-year replacement plan for all infrastructure assets, which should relieve this situation.

Between 1995 and 1999, annual expenditures by the Preservation Division of ProRail/Railinfra beheer were € 650 million per year between 1995 and 1999. Actual preservation work explains only a part of these expenditures: € 365 million were spent on so-called ‘outsourced work’, consisting of M&R and system development/upgrading; the remaining € 285 million were spent on interest, depreciation, salaries and other expenses. Track renewal caused 25% of the ‘outsourced work’.

The four maintenance regions have considerable freedom in planning M&R, but they have to negotiate with the other regions on the exact budget splits. A production planning cycle is therefore used, for category 2 and 3, which starts in November of the year n, two years before the plans are to be implemented (year n + 2). The planning cycle officially starts with the management’s Budget Plan (in Dutch; ‘Kaderbrief’). The plan includes preliminary budgets, based on the (foreseen) results from negotiations with the Ministry of Transport. These negotiations are carried out by the Management Team, which uses indications of required M&R volumes for each technical discipline, such as Track, Signalling, Power Supply, Civil Assets etc. The regions already have lists available with expected M&R volumes for the coming years.
On the basis of the Budget Plan, the Planning Groups in each region start to develop a regional production plan, which contains a list of priority projects and should match the available budget for year $n+2$. The members of these groups (further referred to as ‘the planners’) are responsible for the priority list, but they work closely together with the technical specialists from the Execution Groups, i.e. the groups that will realise the works in year $n+2$. In April of the year $n+1$ a first draft of the national production plan becomes available and is put to the test by the central Finance and Control Department. Modifications to the plan are generally necessary, because the overall budget level usually changes during the negotiations between the Management Team and the Ministry. The modifications are performed in May and meetings between the regions are needed in advance. The production plan for the year $n+2$ is often approved around October of the year $n+1$, although in practice some regions might already have started several projects in order to avoid delays in the first half year of year $n+2$.

It is not hard to imagine that considerable coordination is required to compose a feasible production plan in this setting, which is why regional staff members participate in a number of national boards, which should guarantee the quality of the production plan.\(^{54}\) Firstly, technical specialists from the Execution Groups in each region participate in interdisciplinary Technical Committees (e.g. one for Track, one for Power Supply etc.). These committees discuss developments in the field, determine the need for new R&D, and prescribe standards for planning and implementing M&R. Secondly, the Planning Group Managers participate in the Planning Board, which is responsible for steering the production planning cycle. The Planning Board, chaired by the Deputy Director, has to approve the production plan and present it to the Management Team. Thirdly, the Execution Group Managers participate in the Production Board, which monitors the progress in implementing the Plan and solves practical issues. The chairman is one of the four Regional Directors.

As previously mentioned in Section 2.2.3, ProRail had to cope with rapidly reduced central government funding at the end of the 1990s; this resulted in pressures to reduce the Track Renewal (TR) budget. Between 1995 and 1999 only 90 km of full and partial track renewal was achieved per year; many renewal projects planned for 1999 and 2000 had to be postponed. In 1998, ProRail (Railinfrabeheer) decided to develop a Track Renewal Forecast for the period 2000-2020, based on average lifespan expectations for the track components used on the Dutch network [ProRail/RIB, 1999a]. Figure 6.1 shows the outcome.

A huge gap between realised and apparently necessary renewal volumes came to light. Apart from this being a direct basis for starting a dialogue with the Ministry of Transport to raise renewal volumes immediately, the question arose as to whether the cost-effectiveness of existing renewal practices could be reviewed and improved. This led to the ‘birth’ of the Life-Cycle Management Plus (LCM+) project.

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\(^{54}\) An exception to the decentralised organisational structure is the Telematics Department, which is responsible for the nationwide maintenance of wires and computer systems required for Command, Control, and Communication (CCC).
6.2 The LCM+ project: aims and approach

After the TR issue had become urgent in 1999, the Deputy Director of Preservation, asked the author to develop a plan for reviewing TR practices. A first project proposal was presented in February 2000. In March, the project, which was called ‘Life-Cycle Management Plus for tracks and switches’, or simply LCM+, was included in a draft plan for an Asset Management Programme being developed at that time. This programme would enhance ProRail’s maintenance management skills in the coming years, particularly with respect to developing and using maintenance concepts. The Planning Board accepted LCM+ in May 2000 to be the first project of the new Asset Management Programme. The urgency to start the project had increased rapidly in 2000, as management had decided that around 890 km of Nefit track required priority replacement over the next 8 years (see also Section 2.2.3); this implied that new priorities in planning TR were unavoidable.

During the summer of 2000, a project team was composed. The chairman was also chairman of the technical Track Committee and Planning Group Manager for the Region South. Two planners from the Region South, the Production Plan specialist from the central M&R Finance and Control department, and the author completed the core team. The author refined and extended the Project Plan for LCM+ in close cooperation with this group. A final version was sent to the Planning Board in the first week of September [Swier and Zoeteman, 2000]. The project plan expressed a belief that a more optimised policy for track renewal was feasible. For example, it mentioned the much longer lifespans being realised in North America. The focus of the project would be on tracks and switches only; coordinating the TR policy with policies from other technical disciplines (e.g. the possible clustering of track and overhead line renewal) was considered to be too complicated to be included in this project. The group formulated the following questions to guide the review:
1. Which margins are available in the current M&R criteria and standards, especially the theoretical lifespans applied for the different track components?

2. How can we increase the lifespan of track components without affecting the quality of the infrastructure in the long term?

3. Is full track renewal always the most cost-effective strategy?

4. What is the impact of changes in the Track Renewal Policy to the disruption of the train services on the short and long term?

The plan was accepted in the first week of September, but with a number of changes. The most important change was that the maintenance contractors were not involved in the project, despite the fact that an invitation letter had been sent. The Management Team considered it strategically important for ProRail to first explore these key questions itself as it was closely related to the internal organisation of ProRail, particularly the way that the Maintenance Regions and the central staff work together in the production planning cycle. The objective of LCM+ was, finally, formulated as:

'To develop (technical) M&R solutions for planning track and switch renewals that reduce TR volumes between 2002 and 2010 considerably and are able to flatten the TR peaks in these years. Their cost-effectiveness should be demonstrated in terms of reduced life-cycle costs and traffic disruption'.

Such policy rules were missing in the production planning cycle, which meant that each region might use different criteria for planning renewals. The Director of Preservation expressed his concern to the Track Committee (during its meeting of August 5, 2000) that many renewals were on too small a scale, which would be particularly inefficient for claiming track possessions. An answer was not immediately available; one explanation was that renewal plans had been limited to urgent spots in the network only as a consequence of budget reductions at the end of the 1990s. All in all, it can be concluded that a sense of urgency seemed to exist.

The project team envisioned that four phases would be necessary to meet the objective. The first two were elaborated in a document by the author. Only a vague idea existed on how to realise the last two phases. During the first phase, a list of promising measures would be drawn up, which could reduce expenditures in the short term without affecting long-term performance. This list would be used in the second phase to analyse a number of representative decision situations, referred to as the LCM+ pilots. The advantage of organising regional pilots would be a more critical review of the actual feasibility and practical value of the selected M&R strategies. The third phase would involve 'extrapolating' the outcomes of the pilots for a variety of situations on the Dutch rail network. The idea was to test the feasibility and robustness of the successful M&R approaches by developing a detailed work planning for a main corridor (e.g. Amsterdam-Maastricht); the TOCs would be consulted during this phase. Finally, the impact of the policy revision would be estimated in the fourth phase, resulting in a new Track Renewal Forecast for the period 2003-2020. Figure 6.2 on the next page shows the proposed sequence of the phases and the project timeline.
Figure 6.2: Steps and schedule for the LCM+ policy revision

The planners and technical track specialists from all four regions were invited to participate in a so-called Expert Panel (see Figure 6.3). The (core) project team felt that it was best to involve all regions intensively in the review of their own practices, in order to create commitment to the project outcomes. The regional staff would be asked to develop and review M&R strategies in a number of pilots. Possible data sources, available to the regional staff, are included in Figure 6.3.

Figure 6.3: Organisation and data flows for the LCM+ policy revision
Plenary sessions, to which other knowledgeable central staff members would also be invited as 'independent consultants', would be held to guarantee the completeness of the set of solutions and reliability of the data and assumptions. An additional guarantee, conform the guidelines of Section 4.4, was that the regional teams had to give their evaluations of different M&R solutions prior to each session. The others could then critically review these evaluations, which would hopefully stimulate a 'creative competition' and serious debate. The author would serve as the 'link' between the regions and the core team. This linkage task was to assist the regions in performing the pilots (e.g. data processing and distribution) and to propose an agenda for the plenary meetings.

In September 2000 all preparations were finalised and the project, which now involved around 15 people, could commence. Section 6.3 describes the process that took place during the first two phases of the project.

6.3 Phases 1 and 2: Identifying possible improvements in TR practices

This section discusses the process from September 2000 until January 2001, when the second phase was finished. The necessary modifications to LCCP are briefly discussed first, followed by phases 1 and 2 of the project.

6.3.1 Modifying LifeCycleCostPlan

In advance of the case study, the author revised LCCP. Firstly, a different, simpler estimation of 'penalty costs' for planned and unplanned track possessions sufficed, according to the starting points of ProRail's Life-Cycle Management programme. The 'penalty costs' set by ProRail itself (and not actually paid to the operators), were directly related to hours of unavailability, rather than to train delay minutes; these varied (in 2000), from € 225 to more than € 1100 per hour for a planned possession of less than 9 hours, depending on the transport value of the particular route. A 50% increase in rates was applied for possessions longer than 9 hours and for unplanned possessions, while no penalties were attributed to temporary speed limitations.\(^{55}\) Secondly, the input tables were modified in order to allow more 'entries'; it was expected that tracks to be studied would consist of patchworks of segments, each with different properties (e.g. residual lifespans), contrary to the new HSL line. Entries were allowed for each defined M&R activity and for different life-cycle phases (e.g. expected number of failures within a certain failure time). This provided the opportunity to modify the parameter level after distinguished events (e.g. performed renewals). A time horizon of 50 years was set in accordance with ProRail's LCC policy.

After these changes, it was expected that the LCCP could deal with the input from the regional teams; fewer uncertainties were expected than in the HSL project. ProRail's LCC Calculation Tool (see Section 2.3.1) would be used to verify the LCCP calculations using the

\(^{55}\) N.B.: apart from the penalty rates used in ProRail's LCC Calculation Tool, another metric is also in use between ProRail and the operators, i.e. the Unit of Business Disruption (in Dutch abbreviated as EVB). In theory this unit is not used to 'monetarise' disruption costs. This unit gives an impression of the disruption level of incidents that have occurred, but does not reflect the number of disrupted trains well, particularly in the case of major disruptions [ProRail/RIB, 2003b].
standard settings. Looking back, this expectation proved to be correct, except for the Alphen-Leiden pilot (discussed in Appendix F). The patchwork in that pilot was too much for the LCCP and the pilot was therefore mostly modelled using ProRail’s tool, which required more effort, particularly to perform a similar scenario and sensitivity analysis.

A last addition to the LCCP was made in January 2001, at the end of the second phase. A special module for scenario management was developed to steer the estimation processes of the individual pilots; this had the advantage of implementing the sensitivity and scenario analysis consistently across all individual pilots. Outcomes were presented in the same module through a number of concise tables and plots.

6.3.2 Generating a set of promising life-cycle cost-saving measures

Although the core team had several ideas for promising M&R strategies, it was considered better to use a set of strategies generated by the entire group of people who were responsible for making the project successful. The author proposed an electronically supported brainstorm session and the core team agreed to this idea. Since it would be a ‘different setting’ than usual, this was expected to create a pleasant atmosphere.

The all-day session was held at the ProRail headquarters in Utrecht, using a mobile ‘Group Decision Room (GDR)’ from the Faculty of Technology, Policy and Management at Delft University. This consisted of interconnected laptops, all using a ‘groupware’ programme named Ventana. This allowed participants to submit ideas anonymously and (simultaneously) to comment on other people’s ideas; Ventana stored all these inputs. The author had prepared the agenda and was also process leader, while a TU Delft student provided technical support.

The Deputy Director of Preservation opened the session by noting a direct relationship between the LCM+ project and the just published vision document ‘A Competitive Railway’. The document stated the necessity of focusing ProRail’s processes explicitly on improving the cost/performance ratio of the railway system, since the motorway system had managed to facilitate four times as many transport loads in terms of passenger kilometres per euro invested over the last decade, and that significant improvements were needed. Improvements should be made through both a better utilisation of the network capacity and a lower cost of ownership. Next, the core team’s chairman and the author explained the purpose of the day. The following questions would guide the first part of the programme:

1. What factors significantly influence the costs of ownership, availability and reliability of the railway infrastructure?
2. What measures can improve the price/performance ratio for tracks and switches in both the short and longer term?
3. What are the most promising measures in terms of cost-effectiveness, technical feasibility (implementation time), and market compatibility (acceptance by the Ministry of Transport and transport operators)?

The first question was meant to encourage participants to think outside the scope of their daily tasks. The conceptual model of Section 4.3.1 was presented, and they were asked to submit (via sub-groups) influential factors related to ProRail’s maintenance policy and the
physical, legal, financial and operational environment. This session resulted in a rich set of (perceived) cost drivers and performance killers.

After this ‘warming up round’, the second and third questions aimed to come up with a set of M&R solutions to be used as a reference for the regional LCM+ teams. A list of the 30 most promising measures was derived from a total of 80 generated measures, using an electronic voting system. Figure 6.4 on the next page shows the ranking of these 30 measures, after counting all votes; the outcome is sorted according to the metric ‘cost-effectiveness’. Small standard deviations confirmed that opinions were largely uniform. As the figure shows, most selected measures related to technology and M&R methods; many suggested organisational measures did not appear in the top 30, possibly because the participants were unsure of their merits and feasibility in the short term. Most solutions in the figure are fairly self-explanatory. They are not discussed here; a complete report is available at ProRail.

The day finished with a selection of concrete decision situations in which the proposed set of measures could be tested. Since it was deemed important to represent the diversity in track and switch types and operating conditions within these pilots, the core team had already prepared a list of potential locations. This list was drawn up on the basis of renewal decisions, preliminary submitted by the regions for the year 2002; the projects contributed significantly to the TR budget, which would guarantee that the pilots concerned specific and urgent decisions for the regions themselves.

A list of 10 pilots was accepted and, fortunately, the regional representatives promised to cooperate, as they had not been informed beforehand that they would be expected to do so. The author distributed a report soon after the session, which included all results and agreed actions. The core team proposed reducing the set of solutions further to just those that could show immediate results, i.e. savings. The following topics were suggested for further elaboration: partial renewal (separate renewal of components); longer track possessions; single-track possessions for renewals; high-output renewal trains; life-extending maintenance methods; reusing main-line components on branch lines; and monitoring renewal and upgrading projects for possible synergy effects in the event of combined implementation.

6.3.3 Performing the LCM+ pilots

During the next plenary meeting, each of the regional teams was asked to come up with an initial set of possible M&R strategies for the selected pilots, which was in fact the start of the second project phase. They had received the report on the brainstorming session and Part A of a standardised data checklist (see Appendix C).

During this first meeting, in October, the teams reviewed the alternatives proposed by the other regional teams and several objections were made to proposed alternatives. In the end alternatives remained where the group considered technical feasibility, safety etc. to be assured. The teams were free to use any source of information and expertise, as long as traceable references were made. Remarkably, in a couple of cases, a region could refer to recent, successful solutions implementations, which were heavily debated by the others. After this first meeting, a series of progress meetings took place from November to January. During this period, the author visited all regions a couple of times.
Figure 6.4: Top 30 of measures from the brainstorm session
Clear decision-making rounds can be recognised in the plenary process, in which input and output data were presented and discussed; the author described these rounds in the final project document [Zoeteman et al., 2001]. Assumptions that had been agreed upon during the plenary sessions were documented in the minutes. During the first round the teams developed estimates of residual lifespans, required costs and possessions. Although the pilots generally concerned different situations, there were sufficient opportunities to perform crosschecks between their data and assumptions by considering the differences in the operating conditions. In the Expert Panel, agreement was first reached on the expectations for major M&R works (e.g. necessary tamping and track component renewal). Agreement on data that related to innovative, life-extending maintenance could not be reached. Nevertheless, an information document was composed and sent to stakeholders and other skilled staff members in November.

A second round followed in December, when the regional teams delivered more arguments for their estimates and a first run of the LCCP showed the possible impacts of uncertain input data. In most cases this impact proved to be limited. Most outcomes could also be explained well. The LCM+ core team composed two questionnaires to which the participants responded anonymously. Agreement was reached on the remaining issues at the beginning of January.

A third round in January focused on developing average cost and production speed estimates for long single-track possessions. The core team had proposed estimating the impacts of implementing larger track component renewals (e.g. lengths of 5 km) during weekends or even longer possessions. Agreement was reached in January, although one of the four regions was convinced that lower unit costs and higher production speeds were certainly possible. The core team decided to use the more cautious estimates.

A final report was made early in February, in which the pilots had been classified into two themes, i.e. ‘Life extension and up-scaling of work methods’ and ‘Functionality-based design and instant reuse’. The theme ‘Life extension and scaling up of work methods’ comprised four pilots that were performed by three regions. The first pilot, Sittard-Heerlen, concerned a track section of around 5 km in the Region South, between the towns of Sittard and Heerlen. This section consists of an old Dutch rail type (NP46). This track can still be found on secondary lines and side tracks (UIC Classes 5 and 6; see ProRail [1996] for an explanation of the use of UIC leaflet 7.14 at ProRail). The second pilot, Assen-Haren, concerned an 8 km track section of Nefit track in the Region Northeast. Nefit was still found on 13% of the rail network in 2000. The third pilot, Leeuwarden-Stavoren, concerned a 7 km track renewal on a regional line in Fryslan, a province in the northeast. This is an example of lightly used UIC Class 6 track, which can be found on 25% of the total network. The fourth project, the Alphen-Leiden pilot covered a section of 14 km, mostly consisting of Nefit track of varying ages. This had been installed in a patchwork in between other track types over short distances. Finally, an analysis is included of the potential effects of long, weekend or week, possessions.

The theme ‘Functionality-based design and instant reuse’ comprised five pilots performed by three regions and an OPC (maintenance) contractor, which focused on an optimal track design and reusing main line components on secondary lines. The first pilot,
Amsterdam Switches, considered various solutions for a side-track switch at a shunting yard in the Region Rimcity North; around half the switches can be found at such locations. The second pilot, Eindhoven Switches, looked at several reuse options for a switch to be removed from a station yard in the Region South. The Meppel Switches pilot assessed the life-cycle costs of several switch designs. The Baarn-Amersfoort pilot studied the potential of reusing good-quality Nefit track components at a nearby yard. Finally, a pilot performed by Volker Stevin Rail and Traffic looked at the potential of installing heavier track designs on the Dutch rail network.

Appendix F discusses the outcomes of the two themes, which are visualised through a number of charts. Note that these charts have been included in the usual format used for LCC analysis at ProRail, although their version in the LCM+ report included more detail, i.e. at the level of individual activities [Zoeteman et al., 2001]. However, this was too closely linked to ProRail’s business process and did not improve the readability of this text. Expectations on costs and effects of life-extending maintenance were based on available unit rates and the aforementioned judgements of the Expert Panel. In order to provide the reader with an idea of the input, the lifespan expectations used in the pilots are included in Figure 6.5. NP46, UIC54 and UIC60 are all ballasted track systems, based on the different types of rail. ProRail’s expectations on direct-fastened slab track and embedded rails are also added in the figures. Lifespans vary according to the types of track systems (the different curves) and traffic intensity.

![Image]

**Figure 6.5: Lifespan expectations of ProRail for different track systems [Swier, 2004]**
6.4 Phases 3 and 4: Developing policy rules for track renewal

The core team had concluded in December 2000, when most pilots seemed to have reached a fairly definitive stage, that it should be possible to create commitment to developing a number of TR policy rules. The pilots had provided a fair amount of data, under well-defined assumptions, on the expected effectiveness of various M&R solutions. Most solutions showed reduced renewal volumes as early as 2003, while reducing life-cycle costs by 5-15%. This outcome proved relatively stable under changed lifespans, thus reflecting heavier or lighter conditions.

Developing generic policy rules would, however, require a broad evaluation of factors, such as safety considerations, life-cycle costs, locally available (free) possession time, and required planning efforts. With this in mind, it was deemed best to let those who had a direct stake in these rules decide, as they had the best insight into technical, operational and organisational drawbacks; the Expert Panel and other M&R experts from the central staff were invited to attend a policy workshop on February 9, 2001.

The author prepared a draft workshop programme, which was discussed with the core team. The idea of the workshop was to discuss each pilot individually and hopefully to draw up a number of ‘rules’. It was envisioned that these rules would be fairly rough guidelines for decision-making rather than detailed technical specifications. The workshop approach was tested in a core team meeting in January, which resulted in a number of ‘backup rules’, just in case discussions did not progress well.

6.4.1 The LCM+ policy workshop

The policy session was announced under the ambitious title: ‘Development of a Life-Cycle Strategy for Tracks and Switches’; everyone invited received a programme booklet in advance and was asked to reflect on the following questions:

- Which of the pilot solutions are to be included in the 2002 production plan?
- What do the outcomes of a pilot mean for other parts of the national rail network (comparability in terms of track age, traffic loads etc.)?
- What kind of strategies can be derived in terms of target lifespans, track possession claims and prioritisation of renewal projects for the entire rail network?
- On which scale can these strategies possibly be applied, also considering their acceptability to the Ministry of Transport and the operators?

A detailed programme was prepared. The Deputy Director would open the workshop. The author would then present individual pilot results using the LCCP, after which the chairman of the core team would lead the discussion. Finally, a discussion on the suitability of the production planning cycle would be held.

The agenda was realised as hoped; from the start everyone participated in a lively discussion, which made the ‘backup rules’ superfluous. First, the Deputy Director stressed the importance of having a set of rules for making explicit, transparent decisions in direct relation to the Performance Contract that will define the service to be delivered by ProRail. Further, he
stated that 'it is not acceptable for a railway network with a replacement value of say € 40 billion to have an official policy and standards that do not necessarily reflect the outside practices and vice versa'. The various pilots were then discussed, which resulted in the policy rules included in Section 6.4.2. Two TU Delft students recorded all discussions (see Box 6.2) and were also important assistants in creating a 'relaxed atmosphere'. During the morning breaks, the participants were invited for video interviews, with questions about their daily work and, especially, what they would do if they were the boss of ProRail. The 'results' were shown in an afternoon intermezzo.

**Box 6.2: Part of a discussion around the Leeuwarden-Stavoren pilot (P = person)**

<table>
<thead>
<tr>
<th>P1: The main question is how to deal with these types of lines, which face an uncertain future and have low traffic densities [this person refers to secondary UIC 6 routes in peripheral areas, AZ].</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2: If you install a track system with concrete sleepers and UIC rails, there will be a residual value if the line is closed in 10 years.</td>
</tr>
<tr>
<td>P1: In the past, as many reusable components as possible were transported to these lines.</td>
</tr>
<tr>
<td>P3: That was under different macroeconomic circumstances.</td>
</tr>
<tr>
<td>P4: Is that an argument?</td>
</tr>
<tr>
<td>P3: If more money had been available at the time, this would not have been done.</td>
</tr>
<tr>
<td>P4: So if there is money, than it has to be spent?</td>
</tr>
<tr>
<td>P3: No, but you have to take the circumstances into consideration.</td>
</tr>
<tr>
<td>P4: I think that the budget amount is not an argument.</td>
</tr>
<tr>
<td>P5: You can come to an agreement with the transport company on the rolling stock to be operated on the line and modify your track structure accordingly, can't you?</td>
</tr>
<tr>
<td>P1: So you discuss with the client what to do?</td>
</tr>
<tr>
<td>P5: Yes, and put it into a kind of contract.</td>
</tr>
<tr>
<td>P2: A contract with an operator is also for the short term, a maximum of 10 years.</td>
</tr>
<tr>
<td>P5: Ten years with an option or something like that.</td>
</tr>
<tr>
<td>P4: You can make it a requirement for the next operator.</td>
</tr>
<tr>
<td>P1: We should dare to elaborate even more unorthodox solutions.</td>
</tr>
<tr>
<td>P2: But you always have to consider the short-term investment.</td>
</tr>
</tbody>
</table>

- P1 writes a policy rule on flip-over: Do not completely wear out the main-line components, but reuse them in side tracks and light lines. 'Or should it be formulated differently?' (Etc.)

Finally, the afternoon session was used to consider how the production plan could be better used as an instrument in a life-cycle-based M&R process. At the start, the participants were divided into three sub-groups, which were asked to propose possible changes to the existing production planning cycle, to define the quality properties of the production plan, to identify consequential data needs, and to investigate their current feasibility. The results are included in Section 6.4.3.

Soon after the workshop, the author distributed a report on the conclusions reached that day. First, the agreed policy rules were formulated accurately and coded in several steps. The first version was discussed in the core team, which resulted in a few revisions. The second version was distributed to all participants, who were informed that the core team would advise
the ProRail management that regions opting to depart from the rules should be asked to specify their reasons for doing so. The communication also stated that the application of LCM+ rules required a close study of the outside situation: 'desktop proposals' based on theoretical lifespans and indications from contractors were considered unacceptable. If an LCM+ rule did not deal with a particular situation, then other policy rules would stay unabatedly applicable. All discussions on that day were included in an appendix. The regions were allowed 2 weeks to discuss the comments and provide feedback; this resulted in a couple of suggestions for improved descriptions or definitions.

6.4.2 Policy rules for track and switch renewal

The policy session resulted in a number of policy rules that are presented in the overview below. They may be mainly of interest to the more technical reader, but were clearly the main product of the LCM+ project; they will be best understood after reading Appendix F. The rules were categorised into rules for UIC54 track systems, NP46 track systems, UIC Class 6 lines, track renewal methods, and switches. They were mostly additions to existing policy, except for (a) the rejection of unconditional harmonisation of renewal cycles and (b) the recommendation of a slightly 'lighter' track design on concrete sleepers for UIC Class 6 lines. Apart from life-cycle costs, the developed rules were also assessed separately with respect to traffic disruption and short-term budget need (see Table 6.1 on the next page for a summary).

**UIC54 track systems**

1. Rail renewal is postponed for continuously welded rail (CWR), if the rails have a residual life of 15 years or more. However, ballast bed and sleepers are renewed simultaneously; a separate sleeper renewal is allowed only in the event of a good ballast quality (to be demonstrated by the region). A full, harmonised track renewal remains the best solution, if the residual rail life is less than 10 years.

2. Nefit track must be removed from the network before 2007, except for some regional lines where a later renewal date is acceptable. Installation of Veldermans is not desirable, but is allowed in the event of urgent budget shortage. In that case, large-scale application should safeguard a 5-year postponement.

**NP46 track systems**

3. Worn-out NP46 tracks are replaced with standard UIC54 track on concrete sleepers in a full track renewal; other rules apply for UIC Class 6 lines.

4. Softwood sleepers and jointed rails must always be replaced. Postponing track renewal on hardwood sleepers by 5 years should be elaborated as a decision option. Because the quality deterioration can be monitored well, coils can serve as a safe and effective solution for hardwood sleepers.

**UIC Class 6 lines**

5. The region elaborates two scenarios for worn-out tracks on secondary lines and side tracks: (1) renewal and (2) controlled life extension by at least 5 years. It is the Management Team's responsibility to discuss with responsible bodies whether large investments are acceptable.

6. A leaner track design is installed on Class 6 tracks, with a ballast bed thickness of 20 cm (below sleeper) and a sleeper distance of 75 cm.
7. Reusable sleepers and rails from upgrading projects on main tracks are used as much as possible for Class 6 lines. The regions should undertake timely studies on whether renewals on Class 6 track can be combined with main-line renewals (particularly young Nefit tracks) in order to reuse components instantly.

8. The 'chocolates and screws' solution can be elaborated for reusing Nefit sleepers on little-used NP46 sidings. Sleepers should be in good condition (to be demonstrated by the region) and a careful demolition process is necessary.

Track renewal methods
9. Track renewal is realised with renewal trains, unless the sections method is more appropriate due to local circumstances.

10. Clustering has to be considered if the track sections are part of a patchwork of track sections that still have a residual life. In terms of unit costs, renewal over a stretch of 5 km or more may be the least expensive, but a specific life-cycle cost analysis should provide insight into the applicability of clustering, including the combination with life-extending strategies for deteriorated segments.

11. Slots of at least 9 hours should be claimed for renewal. The region should also elaborate an implementation variant with single-track weekend slots for project stretches over 5 km.

Switches
12. A UIC54 switch with CWR on concrete sleepers should be used on main tracks and heavily used yards; a fixed frog is used for angles of 1:15 and larger.

13. If there are exceptional functionality demands (noise and high speeds), a switch design with a moveable frog is allowed.

14. A UIC54 switch with CWR on timber sleepers should be used on side tracks; if possible, the point machine of the previous switch is reused. New switches must not be installed in side tracks outside the area of central traffic control.

15. Replacing switch sleepers and performing geometric maintenance is sufficient for lightly used side-track switches. Ballast cleaning or renewal is not needed, unless there are subgrade problems.

16. For switches on yards or side tracks that need to be replaced in a few years, the region should actively study whether main-line (usually NP46) switches will be available. If those switches have a residual life of more than 10 years, instant replacement should be seriously considered.

<table>
<thead>
<tr>
<th>Rules summarised</th>
<th>Life-cycle costs</th>
<th>Traffic disruption</th>
<th>Short-term expenditure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Postpone rail renewal UIC54</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>life &gt; 10 years</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Life extension NP46 hardwood</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Clustering renewal on adjacent segments</td>
<td>+/-</td>
<td>+/-</td>
<td>-</td>
</tr>
<tr>
<td>Limited application of weekend possibilities</td>
<td>+/-</td>
<td>+/-</td>
<td>+</td>
</tr>
<tr>
<td>Instant re-use switches and sleepers</td>
<td>+</td>
<td>+/-</td>
<td>+</td>
</tr>
<tr>
<td>Light design UIC Class 6 lines</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
</tbody>
</table>

+ = positive impact
- = negative impact
+/ - = positive/negative depending on situation; situation-specific analysis is needed
0 = negligible impact
Most policy rules prove to be effective for reducing both life-cycle costs and short-term budget needs. However, certain rules, such as clustering of renewals, need some additional analysis in order to determine whether they are effective under the particular circumstances. This also applies to the impacts on traffic disruption – these are usually small, except for the application of weekend possessions, which is a deliberate choice to concentrate disruption on a single point in time; it should only be considered for large renewals.

6.4.3 Requirements for the production planning cycle

The afternoon session revealed that the participants were fairly unanimous in their opinions on LCM+ and the existing organisation of the production planning cycle (PPC). LCM+ was considered an important contribution to the ProRail ‘toolkit’, and the group considered that the existing PPC needed changing in order to:

- ground the LCM+ rules strongly as the ruling policy for TR;
- realise a production plan with a longer planning horizon; and,
- monitor and enforce the plans in such a production plan.

Several serious obstacles to a more life-cycle-based strategy were identified. Firstly, a minimal requirement would be that the production plans for TR are finalised 2 years in advance in order to enable a timely, robust coordination of projects in and between the regions (e.g. for immediate reuse of track components). This was already the starting point for the PPC (see Section 2.3.1), but in practice the available budget remains an uncertain factor during the entire process; a considerable part of the plans are even accepted just a year in advance, which causes serious implementation problems in combination with the 'fond perdu' financing (numerous changes in TR plans, serious underspending of budgets etc.).

A second problem that was recognised by the participants concerned the absence of central coordination, deemed necessary to compose a customer-oriented production plan within the available budget. At the time of LCM+, the regions negotiated among themselves on budget distribution, but worked on their plans independently. Since those plans were accepted without review, they might not result in optimal spending of the agreed budgets and maintenance slots. The coming performance regime would only enhance the need for 'supra-regional' coordination in order to use M&R slots optimally at transport corridor level.

A third problem concerned the absence of consistent data collection and processing standards, procedures and tools for track M&R plans. Workshop participants stated that (apart from little-used side tracks) much useful data should already be available within ProRail (see Table 6.2), though not in an organised, accessible format, e.g. a central production plan database. For example, the production plan does not reveal realised lifespans, which are important for evaluating the effectiveness of past M&R and for improving future budget plans. The regions also use different project scopes, data tools and procedures, despite the main PPC starting point of using uniform asset status files and project information documents. Table 6.2 shows key data that participants would like to have available in a single database, preferably a couple of years in advance.
### Table 6.2: Types of data needed for composing a robust TR Plan

<table>
<thead>
<tr>
<th>Input database Production Plan</th>
<th>Who submits?</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Project scope (km track, # of switches and level crossings)</td>
<td>- Planning Groups</td>
</tr>
<tr>
<td>B Asset data (age)</td>
<td>- Execution Groups</td>
</tr>
<tr>
<td>C Maintenance history and condition</td>
<td>- Execution Groups</td>
</tr>
<tr>
<td>D Relations with construction/upgrading projects</td>
<td>- Planning Groups</td>
</tr>
<tr>
<td>E Analysis of critical resources (such as slots and machines)</td>
<td>- Planning Groups</td>
</tr>
<tr>
<td></td>
<td>- Execution Groups</td>
</tr>
<tr>
<td>F Failure analysis</td>
<td>- Planning Groups</td>
</tr>
<tr>
<td></td>
<td>- Execution Groups</td>
</tr>
<tr>
<td>G ProRail policy and targets (e.g. Nefit and product innovation)</td>
<td>- Planning Groups</td>
</tr>
<tr>
<td></td>
<td>- Planning Board</td>
</tr>
<tr>
<td></td>
<td>- National Track Committee</td>
</tr>
<tr>
<td>H Environment / permits / legal aspects</td>
<td>- Environmental/Legal Groups</td>
</tr>
</tbody>
</table>

Workshop participants concluded that more central coordination is necessary in the PPC, at least for track renewal. At first sight this was a remarkable outcome, given that most of the group consisted of *regional* experts, and that this conclusion might 'endanger' their personal freedom in developing plans. Note that none of the participants would like to return to the centralised structure of the former infrastructure department within the Netherlands Railways. The regions felt that they should maintain the responsibility for the M&R process, and that the national Track Committee should more actively develop and monitor a 'ruling track M&R policy', including the necessary technical standards and criteria. The planners should also cooperate with the track specialists in a national TR board in order to optimally prioritise the use of scarce resources on the network. Having a timely 5-year indicative TR production plan available, with the plans for the next 2 years being fixed, was considered an absolute prerequisite. One sub-group would even like to see a 10-year plan, such as was made by the former NS Infrastructure department (IS8). Finally, the sub-groups had written down a number of terms that they felt should form the basis of the new PPC, e.g. *transparency*, *commitment* (esprit de corps), *reliability* (of the parties within ProRail) and *acceptance* (of the outcomes).

The full implementation of the LCM+ policy was expected to require more planning efforts; it meant that the regional managers should be encouraged to give their staff the opportunity to cooperate. A potential bottleneck could be that a large part of the working hours (by planners and track experts) proves to be spent on other tasks, such as the updating of data in ProRail's SAP system. At the time of the LCM+ project, a couple of regions were already having difficulty in providing estimated TR volumes for the coming years, due to staffing problems. The Track Renewal Forecast from 1999 also proved to be based on outdated data and there was no clarity as to which group or department was responsible for updating. It was therefore concluded that many promises of life-cycle-based thinking are not free. They would require a centrally coordinated, robust production plan and, hence, strong support by the Management Team and (likely) at Business Planning Department level, as this is the department responsible for scheduling maintenance slots.
6.4.4 Developing a track renewal forecast for 2003-2020

The fourth project phase, performed in March and April 2001, aimed to quantify the network-wide impacts of LCM+ in terms of a new track renewal forecast (TRF) for the period 2003-2020. The core team, which had been reduced to three persons (the chairman, the production plan specialist and the author), was mainly responsible for this phase. They consulted the regional experts only in order to verify whether they believed assumptions on the network-wide applicability of LCM+ rules to be (more than) sufficiently cautious. Since the applicability of LCM+ had been extensively discussed in the policy workshop, this was considered a reasonable approach; the regional staff needed time to finish the 2002 production plan.

It was soon discovered that the tools available prohibited a detailed and complete insight into the network-wide impacts of LCM+. The main problem was the absence of a computerised planning system, in which the clustering of TR could be defined in a number of ‘if-then’ rules; without such a system, any estimation would be no better than guesswork. Obtaining quickly usable data on track lives from ProRail’s SAP system also proved to be infeasible, as it was impossible to change the output requirements ourselves. It was therefore decided to use the MS Excel spreadsheet files that were used for the Track Renewal Forecast (TRF) of 1999; this spreadsheet was in fact only a list with all track systems on the network and their years of installation.

The use of the former TRF estimation had a number of pros and cons. Clearly, the main advantage was that the estimation was already available and only needed a calculation layer on top of the 1999 outcomes. This approach would also show precisely the changes that an LCM+ measure would bring about. A main disadvantage was that several LCM+ rules were difficult to include. Rules related to the clustering of TR works and reusing Nefit sleepers and main-line switches could not be included at all, while the prescribed light track design could only be applied to secondary lines, and not to side tracks. The reason was that side-tracks costs were only included in the TRF estimation as a mark-up to main-line costs. An average cost rate had to be applied to all forecasted renewals. A final disadvantage was that all data originated from January 1998, when the SAP system was introduced in ProRail; however, it was known that many changes had occurred over the last few years due to upgrading works. Several tracks therefore needed to be removed from the list, but this updating would take too much time. The aforementioned facts made it likely that the estimation would result in too-high renewal volumes and underestimated effects from LCM+.

Nevertheless, it was decided to be cautious in estimating the applicability of the other LCM+ rules. Postponing rail renewal was assumed in only half the cases where the residual rail life was more than 15 years; an unfavourable unit cost was also applied to the separate rail renewal. The ‘coils’ rule for NP46 track was only applied to 20% of the cases. The rule for manually operated switches outside the central traffic area was applied in only one-third of the cases; a reusable switch or, even, a new switch on timber sleepers were assumed for the remaining cases (one-third of the cases each). The use of weekend possessions was assumed for 10% of the renewals, while in 40% of the cases the standard 9-hour time slots were assumed and, in the remaining cases, even 6-hour slots were used – this meant that there was not a significant change in track possession time, compared to existing practices. Finally, the
unit costs for all switch renewals and main-line track renewals were modified to reflect the use of renewal trains and switches on concrete sleeper as well as the latest insight into supplier cost levels.

Under these assumptions, LCM+ indicated the possibility of reducing required renewal volume over the years by approximately €20 million per year (see Figure 6.6); the extra costs for life-extending M&R were deducted from the savings in renewal expenditures. Figure 6.7 on the next page shows the impacts of the individual LCM+ rules, according to the assumptions. The changes in unit costs for track and switch renewal have the strongest impact as they are applied to all renewals.

The impact of the decision to remove all Nefit tracks over the next 5 years is shown separately in the figure; when comparing the different forecasts, one can see that they would have needed replacing anyway over the next 10-15 years. Moreover, it can be seen that the deviation from the 1999 forecast is small after 2015 due to postponed renewals. Figure 6.6 contains only the effects on ProRail’s out-of-pocket expenditures; the effects should be more favourable for the government as a whole because of favourable interest effects. Note that the added value of LCM+ as an instrument to level out renewal peaks over the years could not be simulated in the TRF, as this would require a computerised planning system.

Once the forecast was finished, the author composed the final report in April 2000 [Zoeteman et al, 2001]. This report included all project details and the policy rules, with indicative graphs on life-cycle cost impacts and break-even points. The following section discusses the conclusions and recommendations from the report.

![Figure 6.6: Track Renewal Forecast 2003-2020 after LCM+ (mio = million)](image)
6.5 The LCM+ project: presenting the outcomes to stakeholders

The report was distributed and presented to the key stakeholders in May 2001. The following sections discuss its conclusions and recommendations, plus the responses received from the direct stakeholders.

6.5.1 Key conclusions and recommendations

First of all, the report answered the research questions presented in Section 6.2. The project had demonstrated that there were probably considerable margins for improving TR practices and efficiency in possession claims. Planned expenditures for the coming years – unlike those realised between 1995 and 1999 – can be reduced in the short term through a smart and timely planning of projects, using the LCM+ policy rules, without affecting infrastructure quality and availability. However, LCM+ should not be seen as a simple “economising trick”, but as a tool for improving the quality and prioritisation of renewal works. The key to this approach is to take local, functional needs as the point of departure, instead of sticking to harmonised renewals and theoretical lifespans.

A number of recommendations were made to the Planning Board and the Management Team. A well-supported implementation of LCM+ in the next 2001/2002 planning cycle was recommended being a necessity for ProRail. Recipients were asked to approve the LCM+ outcomes in an official memo before September 2001. The report also contained proposals for enhancing the robustness of the track renewal production plan. The implementation of LCM+ should be supported in the following ways:
1. A ‘living’ policy for track renewal. LCM+ was seen as a first step, but the LCM+ rules should be periodically evaluated and refined based on information obtained from realised M&R works, studies of innovative M&R methods (worldwide), changes in ProRail’s performance targets, and traffic conditions on the network. Furthermore, the LCM+ project did not cover the technical judgements that underlie M&R work proposals or the effects of new preventive maintenance strategies during the life cycle. It was suggested that the central Technical Department (in Dutch: ‘Productbeheer’) should play a key role in research on improved M&R strategies and technical standards. A practical approach would be to start with compiling lifespan statistics, a neglected activity at the time of LCM+. Grinding strategies such as those applied in North America and Japan should also be judged according to their merits. Finally, it might be useful to try and integrate the LCM+ track renewal policy with M&R approaches to Power Supply and Signalling (e.g. combined renewal projects).

2. Contingency measures for LCM+ in daily decision-making. Mechanisms should be included within the organisation to control the application of the LCM+ rules and to stimulate life-cycle thinking. Soft factors (such as loyalty) were considered equally as important as hard factors (such as completeness of the empirical data set). A number of specific actions were recommended:
   - *installing a permanent Track-wide Board.* Open, constructive discussions within this board should stimulate the application of LCM+ across the regions and guarantee an updated TR policy. Commitment by regional executives was considered a prerequisite, because of the required work time;
   - *installing a programme coordinator for TR.* This coordinator should be qualified to assess the submitted proposals on their necessity and cost-effectiveness and should function as an intermediary to management;
   - *a reward scheme for outstanding findings.* For example, the regions should be granted some of the realised savings from innovative solutions in order to use them for other necessary projects;
   - *developing decision-support tools for TR.* Regional staff should be actively supported in evaluating various M&R strategies and options and in submitting consistent and complete data for the production plan. An ‘ECOTRACK-like’ system was suggested to remove the main data analysis obstacles. However, since implementation of such a system would take time, the report proposed starting with software that could make simple visualisations of the TR plans on the network.

3. Developing a centrally reviewed production plan. The Planning Board should be a strong supporter of LCM+ for a more centrally coordinated production plan. The following process design was suggested:
   - listing and visualising the renewal proposals for each transport corridor (before September by the regional staff);
   - reviewing plans in relation to the LCM+ rules in order to check their necessity and to develop coordinated M&R strategies (interregional activity, before the end of October);
   - assessing proposed alternatives on merits and drawbacks (by regions, in November);
   - prioritising projects and developing ‘production plan scenarios’ based on different possession regimes (interregional activity in December and January);
   - elaborating a final, national production plan (before April).
6.5.2 Reactions by the stakeholders

During April and May the results of LCM+ were presented to the key stakeholders, i.e. the regional planners and track experts (April 12); the national Track Committee (April 26); the Planning Board (May 2); the Production Board (April 26), and the Management Team of the Preservation Division (May 8).

The Planning Board, being the main sponsor, expressed the outcomes to be highly important. The Planning Board offered to confirm its commitment in a letter to the technical Track Committee. At that time, all technical committees would just be asked to better specify their technical standards and policy in a single document. LCM+ would be included in the format for Track. In addition, the LCM+ report would be added to the documents presented to the Ministry of Transport for an audit of the Preservation Division (ongoing at that point in time). Finally, the Planning Board would continue to sponsor the implementation of LCM+, and asked that it should include a number of workshops to demonstrate the LCM+ approach to as many staff members as possible, including those working in disciplines other than Track.

The Production Board stated to be impressed, but made two comments on the outcomes, including the realisation that a more constant, flat Track Renewal production volume would require more attention in the coming years. In this respect LCM+ could serve as a helpful tool, but would not directly solve the problems due to the massive renewal of Nefit track. The Production Board concluded that ProRail's track renewal policy, including LCM+, is still in conflict with the available funds, and that monitoring of LCM+ assumptions and expectations is a prerequisite for guaranteeing the validity of the 'LCM+ methodology'. The Management Team of the Preservation Division also responded positively, stating that they would rely on the Planning Board to ensure adequate implementation. LCM+ policy would be included as one of the starting points of the Budget Plan for the coming year.

In August the LCM+ core team presented an implementation plan to the Planning Board, entitled 'The Production Plan as an instrument for Life-Cycle Management'. The key starting point in this document was that the regions needed to be challenged by putting their TR plans to critical tests at a central level. The regions would have to present their (preliminary) plans to the other regions 6 months earlier, i.e. in September, which would provide sufficient time to review these plans and develop an optimal national prioritisation. Central staff would screen the regional plans, after which a discussion would follow in plenary meetings. Four topics were elaborated in the document, i.e.:

- including LCM+ screenings in an early stage of the Planning Cycle;
- installing a formal Track-wide Board of regional planners and track experts;
- guaranteeing the actuality of the LCM+ policy rules in the future; and
- introducing the LCM+ approach to other technical staff and disciplines.

After a significant revision the Planning Board accepted the proposal early in September. Softer incentives to stimulate LCM+ based thinking in the regions were suggested rather than explicit screening tests. Regional staff should be stimulated through a review process, in which colleagues from other regions would ask for explanations of their plans ('colleague checks'). Furthermore, discussions should not directly result in an imperative advice for the regions, also given the last-minute changes that occur in the available TR
budget. The Board would consider a more stringent approach if the softer incentives did not function well in the coming year. The following section discusses how the modified plan was put into practice.

6.6 Implementation and use of the LCM+ policy rules 2001-2003

This section provides an overview of the use of LCM+ up to January 2004, which is crucial for judging the project on its merits. Section 6.6.1 discusses a number of direct R&D spin-offs, while Section 6.6.2 describes the use of LCM+ in 2003 and 2004.

6.6.1 Developing user-friendly decision-support tools for LCM+

A number of R&D tasks were undertaken, although the core team had decided to concentrate its efforts on using LCM+ in the new PPC and leaving suggested research to others, mainly the Technical Department. In November, the author developed a user-friendly quick-scan tool, named LCM+ Easy Estimator, which had been requested by several participants. The tool determined break-even points and potential savings for the following types of decision solutions:

1. Postponing renewal of deteriorated tracks (a general model).
2. Postponing NP46 track renewal, using coils.
4. Postponing UIC54 rail renewal.
5. Clustering renewals on adjacent track sections.
6. Choosing a possession regime.
7. Reusing main-track components on side tracks and branch lines.

Remarkably, it proved possible to simulate the variety of decision situations in rather basic models, using insights from the LCM+ pilots. For example, costs of maintenance or non-availability that rarely influenced a particular decision could be deliberately left out of the models; information on the factors left out of the analysis was included in the user manual. The Easy Estimator could only be used under a number of conditions; outcomes were not valid for lifespans shorter than 25 years and deviated a little from ProRail's LCC Calculation Tool for lifespans over 50 years. As such, the Easy Estimator needs only 5-10 inputs per decision to present indexed life-cycle costs; the standard renewal option, i.e. direct, complete, unclustered track or switch renewal with new materials, is given a value of 100. Figure 6.8 on the next page shows an example of rail renewal postponement.

Finally, an ArcView GIS (Geographical Information System) application was developed, which was able to visualise all kinds of asset and production planning data from the SAP system, in the absence of a computerised maintenance planning system. Within 2 months, the application worked fairly satisfactorily: the TR Forecast, the production plan, line characteristics, installed track types etc., could all be visualised (see Figure 6.9 on the next page for an example).
Figure 6.8: Full vs. partial track renewal decision (ballast and sleepers only)

Figure 6.9: Indicative TR Plan 2003–2007 for the Netherlands as of 2002
The author also supported the feasibility study for ECOTRACK (see Section 2.3.4), which partly focused on the role a computerised maintenance planning system could play in supporting the application of a central policy such as LCM+. Although an in-depth trial was not held, it was concluded that most LCM+ rules could certainly guide the computerised selection of necessary track M&R [Jovanovic et al., 2002]. However, since 2002 ProRail has not taken further action to introduce computerised planning systems for track M&R. The following subsection discusses the results of introducing LCM+ in the planning process for track maintenance and renewal.

6.6.2 LCM+ in the production plans for 2003 and 2004

Implementing LCM+ in the 2001/2002 production planning cycle (PPC) was considered most important; the core team took responsibility for the implementation and the author participated as secretary for LCM+ during the PPC. First of all, the results of LCM+ and the approach taken were presented in a series of lunch lectures for the regions as well as central staff, including the Management Finance Team and the Innovation and Business Planning departments. These presentations took place between October and December, and were also visited by staff from other technical disciplines, as recommended by the Planning Board.

The first activity in the new PPC for track and switch renewal was a ‘comeback day’ for regional planners and track experts on September 27, which would now together constitute the Track-wide Board, being responsible for reviewing their own (initial) plans in order to learn from each other and improve the national production plan. The day consisted of a number of activities meant to facilitate the shift towards a permanent Track-wide Board. The first part of the day was used to provide an update on developments around LCM+ since April 2001. This author then presented the results of anonymous interviews held during the summer. These are discussed in detail in Chapter 7, but an important finding was that all had highly valued the broad range of solutions analysed during the project and the insights obtained on the effectiveness of those solutions. The participants felt that LCM+ had created a fairly strong commitment and an improved mutual understanding. However, there were mixed feelings on the commitment of central and regional managers, who had not participated. During the presentation, the author also gave a playful analysis of the general attitudes of interviewees with respect to implementing LCM+ (see Box 6.3 on the next page). People could be grouped into ‘hardliners’, ‘conservatives’ and ‘liberals’, each having different ideas on the way LCM+ should be used; this evaluation was only meant to initiate a discussion among participants on their expectations for the coming year.

Although some participants expressed their disappointment in the way the implementation was intended (i.e. the lack of clear review rules), all agreed to present (at the next meeting) an evaluation of the use of LCM+ rules in their preliminary plans for 2003.

The second meeting was on November 22 and was mainly intended for group review and discussion. Two regions had performed the assignment and this provided some insight into the scale with which LCM+ rules were incorporated into their plans. For one of these regions significant savings could be derived from LCM+. The gaps in the ‘coverage’ of LCM+ were also visible; rules for direct-fastened tracks, curves, level crossings, bridges and accompanying transition zones were missing. Several different uses of the rules were discussed; e.g. combining the instant reuse of NP46 switches in side tracks with the
systematic removal of these switches on essential main-line locations. Nevertheless, it was disturbing that two regional teams had not found time to perform the exercise. The core team stated that regions complying with LCM+ would be released from the obligation of submitting project-based life-cycle cost studies; it was hoped that this might provide some stimulus. The regional experts were again asked to include the realised lifespan in each project proposal (if the plan were to be implemented) and the applicable LCM+ rule.

**Box 6.3: Typical attitudes on the introduction of LCM+**

<table>
<thead>
<tr>
<th>Attitude</th>
<th>Opinion</th>
</tr>
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</table>
| **Hardliners** | - 'At a certain point in time you have to enforce the application of the policy in practice.'  
- 'The control cycle of Deming – plan, do and check – has to be closed.'  
- 'Independent staff should screen the proposed projects for the production plan.'  
- 'The production plan should enable benchmarking of the regions’ performance.' |
| **Conservatives** | - 'Have trust in our craftsmanship. Everyone wants to meddle in Track Renewal.'  
- 'Our chicken/egg problem is that the Policy Plan of the Management is not finished on time.'  
- 'No flexibility is designed into the process of requesting M&R slots; that should be dealt with.'  
- 'We already apply a part of LCM+ implicitly, but we have to deal with a complicated reality.' |
| **Liberals** | - 'Studying new M&R solutions with the other regions is a good idea.'  
- 'After LCM+, we started more research and we have already come up with better solutions.'  
- 'Give the regions rewards for using LCM+.'  
- 'The best approach is to give us a fixed budget, based on the amount and age of our infrastructure.' |

The interviews made clear that experts and managers hold varying opinions on ways to stimulate life-cycle-based track renewal through LCM+. Three different attitudes were found.

The third meeting was held on January 17, 2002, when an overview of the application of LCM+ rules was still available for only two regions. These regions had added the requested data to the regional production plan, which provided insights into the applicability of the rules and the realised lifespans. A rather diffuse 'landscape' of realised lifespans came to light; some tracks and switches were replaced up to 20 years or, incidentally, even 35 years in advance of their theoretical life, while others had passed this date by 10-15 years; jointed NP46 switches and Nefit track in particular were often replaced 'too quickly'. The comparison was distorted in several ways and therefore actually still impossible. Firstly, the SAP Asset Register still contained the theoretical lifespans dating from 1993; they needed to be modified according to the expectations agreed upon in 1999. Secondly, there were faults in the classification of the infrastructure in terms of traffic loads, especially due to changes in use over time. Thirdly, recent tonnage data was not included in the system. Finally, replacements were due to upgrading projects on the infrastructure. Despite the diffuse outcomes, it was concluded that composing lifespan statistics could become a useful source of insight into driving factors for renewal decisions. The chairman wanted to reconsider which steps should be taken, because lack of cooperation would endanger the objectives of LCM+ implementation. The two regional teams that had not been able to provide the requested information stated that LCM+ had no priority in their regions; they were, nevertheless, asked to submit the data next time.
During the following meeting (March 14), a third region provided more accurate data on realised lifespans; however, in the meantime the LCM+ core team had decided to change the approach to reviewing LCM+, since there was no time left for in-depth investigations. They proposed that the regions work in pairs to organise 'colleague checks'. Two pairs of regions were proposed, which were relatively comparable in terms of numbers of switches, yards, level crossings and branch lines, i.e. the Rimcity regions and the two remaining regions. The test would result in a motivation for budget-consuming projects based on 'plea and counter-plea': realised lifespan, LCM+ rule, critical comments by the other region and the conclusion on how to use these comments would be defined on a single A4 sheet of paper. All these A4 papers would be added as appendices to the 2003 production plan. Such a check proved unacceptable to most regional teams, since they needed all remaining time to finish their production plan on time, and they did not expect much result from such a check. It was finally agreed that the regions would finish the previous assignments as much as possible and that three regions would meet on April 11 to review each other's plans in the presence of the Production Plan specialist.

The last meeting on the 2003 production plan took place on April 25. This concluding day proved to be rather fruitful, especially thanks to the preparatory meeting of the regions on April 11. A number of shared starting points had been agreed upon; e.g. it had been acknowledged that an early renewal of NP46 tracks and switches did not comply with LCM+. Further, LCM+ would be applied, irrespective of whether projects had already been engineered differently. An overview of the projects that were performed according to LCM+ rules could be composed; this concerned about half the entire TR budget for 2003. The presentation by the regional staff on their approach taken for 2003 still revealed considerable differences between the regions. One region stated that LCM+ had become part of the Regional Management Contract, while two regions admitted that LCM+ had not been sufficiently considered due to urgent staffing problems. A management request to supply a plan on how to reduce the number of disruptive failures by 40% over the next 3 years and the urgent problem of Rolling Contact Fatigue (RCF) had taken all their efforts. Their reasons were considered legitimate, and the core team thanked everyone for their efforts. The core team promised to reconsider its approach, given the current misbalance in time, resources and information requests, while all agreed that the LCM+ rules would become a standard reporting element for the 2004 production plan; the data would also make it clear whether new or reusable components were used.

The next PPC started in September 2002: the core team had elaborated a different approach, which meant that the regional budget distribution was fixed in advance (in percentages of the total, but not in absolute values). The fixed TR budget distribution to each region was presented in a plenary meeting on August 29. The distribution was based on the average share of each region in the TR Forecast during the years 2003-2007, including the cautiously expected savings of LCM+ (see Section 6.4.4). The extent of the application, to which the LCM+ rules would be further utilised, was left to the regional staff; however, they had to deliver LCM+ application data, as agreed in April. This approach seemed the fairest as

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56 RCF concerns all rail defects that start on the surface of the rail due to heavy, dynamic loads. Head checks (that start as small cracks but have the potential to quickly develop into a rail break), are the most serious manifestation (see Section 2.3.2).
long as fundamental changes in the PPC had not been made. The Track-wide Board and, subsequently, the Planning Board accepted the fixed budget distribution, despite the fact that it was based on the outdated TR Forecast; the Planning Board asked the Track-wide Board to study how these ‘inaccuracies’ could be resolved. The 2004 production plan was realised as such, while the LCM+ core team had decided not to actively steer the process anymore.

6.7 State of the art in LCM+ and track renewal planning

This section provides a reflection on the state of the art of track renewal planning and the current role and relevance of LCM+, starting with a brief overview of key events in the TR policy arena since 2001:

1. In January 2002, new penalty rates for LCC were adopted within ProRail, which were more than four times as high. The author recalculated all LCM+ estimates, which showed that weekend possessions for main lines (Classes 1 to 4) would now be barely favourable.

2. In March 2002, it became clear that the ‘coils solution’ in the Sittard-Heerlen pilot was more expensive than expected. This was reason enough for the region not to make further efforts at that location; nevertheless, it was decided to maintain the LCM+ rule, as it might still be feasible at other locations.

3. In March 2002, the results of a delayed LCM+ pilot also became available. Tests, performed by the research institute TNO, had shown that the lifespan expectation for duoblock concrete sleepers, installed in the 1970s and 1980s on main track lines, could be raised from 30 to 40 years. However, this required a ‘midlife’ treatment to replace the fastenings and rubber pads.

4. In April 2002, results of a pilot using a new restoration method for Nefit track, performed by the Region South in the province of Zeeland, were assessed on their life-extending effect. The sleepers had been renovated using new baseplates and a highly mechanised milling process. The low replacement costs and the good resulting quality (i.e. expected residual lives of 10-15 years, depending on track age) would make considerable savings in life-cycle costs possible. The large impact of these new findings was another reason for suggesting a revision of the 1999 Track Renewal Forecast. Since Nefit and duoblock sleepers would consume large parts of the TR volumes, a drastic reduction in TR volume was considered possible, particularly between 2006 and 2014 (see Figure 6.10 on the next page).

5. In the summer of 2002, a dispute emerged with the Labour Inspectorate on labour safety with regard to single-track renewals, with traffic continuing on the adjacent track. Single-track possessions were considered an unacceptable work method, which meant that scenarios based on single-track renewals were no longer an option.

6. In 2002 and 2003, several pilots (such as the Baam-Amersfoort pilot) were realised as planned while, since 2003, LCM+ rules have also been applied to new projects. Rahmenschwellen was also successfully tested for supporting insulation joints.

7. In 2004, the Leeuwarden-Stavoren pilot was realised in a full week possession. The low construction costs were realised as planned, but unexpected problems occurred, as reusable rails were not of a sufficiently high quality, due to mistakes in selecting the rails during the execution [information supplied by R. Vosswinkel]. All in all, there are reasons to review the assumptions of this pilot (see also Appendix F).
8. A new development in 2003 concerned an audit of the criteria applied by the regions in selecting TR projects. The audit showed that a substantial number of inspected projects, planned for 2004, could be postponed, by about 5 years. Technical criteria and checks on the prioritisation of TR projects were found to be insufficient or absent [ProRail, 2003a].

9. In 2004, ProRail developed a first-ever multi-year renewal plan for the entire railway infrastructure. Although an enquiry in the regions resulted in considerable higher funding requests for track renewal (compared to any previous forecast), it was decided to use the latest forecast as a basis for this plan (see Figure 6.10, 'LCM+ insight 2002') [information supplied by J. Swier]. A process to better control the quality of the track renewal plans and an updated track renewal forecast will, hopefully, result from a new project initiated by ProRail and TU Delft, known as 'Yardstick Track Renewal'. This project will review (in 2005) the criteria underlying the TR proposals; its main objective is to develop a strict and proper set of (technical) criteria for prioritising track renewal plans [Zoeteman, 2004].

10. Currently, plans are being elaborated to reorganise the regional departments for planning and realising maintenance and renewal (see Sections 2.3.1 and 6.1). The technical specialists will transfer from the Execution to the Planning Groups, while the Execution Groups will probably 'merge' with groups which are currently responsible for (regional) upgrading projects. This will, hopefully, give the regional Planning Groups more time and resources for analysis [information supplied by K. Wijbrandts].

![Figure 6.10: LCM+ Track Renewal Forecast including the 2002 insights [Zoeteman et al., 2004]](image)

All in all, some success was achieved in implementing LCM+, but it is clear that a systematic process of applying, monitoring and refining LCM+ and other (technical) rules, as a 'living policy' for track maintenance and renewal, is missing. The planning process for track renewal is, in general, still far from a stable environment; systematic analysis is sacrificed for urgent, daily issues (‘fire-fighting’). Main difficulties can be summarised as:
the maintenance regions cannot reserve work capacity to analyse their production plans with respect to possible ‘LCM+ gains’. This analysis also proved more difficult than expected, due to data problems (e.g. dates of track installation);

- events in the realisation of the LCM+ pilots and in the policy arena around railway maintenance affected the usability and effectiveness of some of the LCM+ rules;

- technical criteria for triggering and prioritising track renewals, which should complement the ‘economic’ LCM+ rules, are inconsistent or absent at the moment;

- the LCM+ rules do not cover yet all track systems and still have a relatively rough character.

In a next step, the LCM+ rules can be further refined to rules for track systems under specific, well-defined conditions (concerning track age, transport loads, subsoil conditions and alignment/radii), for example using actual data from ProRail’s new, promising traffic load measurement system, Quo Vadis. Likely, the analysis of the robustness of such technical and economic rules can be improved through the use of stochastic LCC models.
7. Evaluation of the Case Studies

LCC-based support was provided in three cases: (1) the appraisal of track systems for the HSL South, (2) the search for ‘cost-effective reliability improvements’ for the HSL South and (3) a review of existing maintenance practices. This chapter uses these studies to formulate an answer to the third research question: *Is a decision-support approach able to have courses of action developed and adopted, which are expected to be more cost-effective (over the system life-cycle)?*

Section 7.1 discusses the way in which the evaluation was set up. Sections 7.2 to 7.4 discuss the subsequent cases, while Section 7.5 compares and integrates findings from the individual cases; it results in a ‘rich picture’ of the effects produced by the support provided, in relation to a set of organisational conditions.

7.1 Evaluation method

Because of the author’s active participation in the cases, ex-post interviews with participants were selected as the primary source of information (see Sections 1.3 and 4.4). These interviews should provide an indication of the effects in terms of the quality of decisions (richness of decision input, cost/quality ratio) and the decision-making process (legitimacy of decisions, process for progress). A set of effectiveness indicators was therefore derived in Section 4.1.3, based on the theory of decision support in multi-actor environments.

The advantage of interviews is that they provide traceable chains of evidence, with regard to the effects of the decision support on the decision-making process. This safeguards the objectivity and transparency of the research. Evidently the result should give an indication of the effectiveness of the LCC-based approach, as perceived and stated by immediate stakeholders. It is therefore possible that interviewees express overly optimistic or pessimistic views; this is verified, as far as possible, with the process descriptions in Chapters 5 and 6, which also provide data on events after the interviews were held. This is possible because the process descriptions and the interviews form two independent sources of information.

At the end of each case study, the author composed a list of people to be interviewed, in cooperation with the study initiators who assisted, where necessary, in inviting these individuals. Between 10 and 16 people were interviewed per case study. In the HSL cases, it was decided to include a couple of people who had audited the decision-making process, in
order to enhance the range of perceptions; however, since they were not involved in the study itself, they could not supply complete assessments. A couple of people could not be interviewed because they had moved abroad, but there is no reason to assume that their absence distorts the general findings, though some opinions, unfortunately, may not have been captured.

A distinction can be made between various categories of respondents and this has been added to the tables with outcomes in this chapter. This concerned decision makers, (indicated in the tables as ‘D’) and experts (E), who participated to provide data and knowledge. There were also a few reviewers (R), i.e. people who were commissioned to review the quality of the study, and a few people who had participated as both decision maker and expert (B). A second distinction can be made between those who were highly involved (H), those who were only involved now and then (M = ‘medium’) and those who followed the process at a distance (L = ‘low’ involvement). This was based on the indication of time and effort spent on the issue, as expressed by the respondents themselves.

The evaluation interviews consisted of a scorecard, to be filled in by the participant, and a structured set of questions that were intended to extract the underlying thoughts from the participants (see Appendix B). Each question reflected the distinguished criteria for establishing whether or not the LCC support had improved the decision-making process (see Section 4.1.3). A five-point scale was used, viz.:

- 1: participant strongly disagrees, i.e. support had highly negative effect;
- 2: participant disagrees;
- 3: participant is undecided, i.e. effects are missing or unclear;
- 4: participant agrees; and,
- 5: participant strongly agrees, i.e. support had highly positive effect.

Since the interviewees do not represent a sample from a larger population, the percentage of positive scores directly indicates whether the outcome should be considered significant. Nevertheless, statistical inference, i.e. the quantile test as described by Connover (1980), was helpful. This test can be used to assess whether outcomes are significantly positive, i.e. non-random, by comparing outcomes to a binomial distribution. Positive (scores of 4 and 5) and non-positive answers are distinguished. The binomial distribution describes the theoretical probability of a given number of positive outcomes from a set of independent experiments, where the probability of a positive outcome in the individual experiments is constant. In this case, each interview is considered one experiment with a random probability of 40% that the interviewee would give a score of 4 or 5.\textsuperscript{57} Table 7.1 shows the probabilities of positive outcomes for a confidence level of 95%. The grey cells show the required minimal number of positive answers (k), given the total number of interviews (n). This quantitative assessment was only one of the ingredients supporting the evaluation; as previously mentioned, qualitative interview questions were also designed to reveal the ‘invisible mechanisms’ that were at stake in the decision-making process.

\textsuperscript{57} It should also be assumed that the scores at least fit an interval scale; this is considered an acceptable assumption, since the interviewees were asked to use the score scale as a uniform scale.
Table 7.1: Probabilities according to binomial distribution

<table>
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Considerable attention was paid to presenting and using the answers in a systematic and transparent manner. First, separate conclusions were developed for the various case studies, before the collected evidence was integrated into an overall ‘picture’ of LCC effects. Opinions were grouped per case study as follows:

1. Timing and positioning of the study: interviewees reflect on the way the study was introduced and embedded within their organisations.
2. Work approach and methods: interviewees reflect on the quality and usability of the LCC-based approach, as used in the case study.
3. Alternatives studied: interviewees reflect on the alternatives studied or developed during the process (e.g. completeness of the set of alternatives).
4. Impacts of the decision support: interviewees reflect on the impacts that the study had on the ongoing decision-making process.
5. Conclusions: key findings of quantitative scores and the expressed opinions are combined into a set of conclusions for each case study.

When preparing this chapter, all expressed views were first listed for each of these aspects in order to analyse their coherence. Findings have been summarised for the purpose of readability. Quotes by individual interviewees have been added where these summarise the general feelings of all interviewees or where they reflect a divergent view among all others; longer quotes have been centred in italics, which is just a choice of style. Finally, the answers also provided a key to explaining individual scores; in particular, the causes of some negative scores were sought, as they might resemble unwanted impacts of the LCC-based approach. A code is used for each interviewee, with a prefix referring to the particular case study: ‘TS’ for the HSL track selection, ‘S4’ for the HSL system availability study and ‘TR’ for the track renewal policy study at ProRail/RIB.

7.2 Perceived effectiveness in the HSL Track Selection case

This section analyses the effectiveness of the LCC-based approach during the Consultation Phase of the HSL tender, as perceived by the participants in the decision-making process concerning track design (see Sections 5.3 and 5.4). Thirteen people were interviewed in the spring of 2000, which was more than 6 months after the case study and 2 months after the Tendering Phase.
Table 7.2 shows their quantitative assessments. The approach is apparently valued most for increasing the richness of the information that was available to decision makers within the consortium and for helping to achieve some progress in the process (‘sense of urgency’). While being helpful for these aspects, it did not seem to have significantly improved the set of alternatives, the cost/quality ratio and legitimacy of the choice, or the decision time. An explanation might be that the increased information richness and manageability was still not sufficient to answer the questions satisfactorily; another explanation might be that process aspects may have hindered the use of the analysis results; the process-related indicators are surrounded by controversy (reflected most in the scores for relationships and mutual understanding, with a standard deviation of more than 1 point). Probable causes for these scores are included in the text below.

### Table 7.2: HSL Track Selection Case (bold = assessed significantly positive)

<table>
<thead>
<tr>
<th>Aspects</th>
<th>Operational Indicators</th>
<th>Interviewee</th>
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<tbody>
<tr>
<td></td>
<td>No. 1 2 3 4 5 6 7 8 9 10 11 12 13</td>
<td>Role E E D E E E E E B R D D R E</td>
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<td>Involvement H H M H M M M M L H L L M H</td>
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<td>Richness of inputs</td>
<td>Insight into situation/alternatives 4 4 3 4 4 4 4 2 4 3 4 4 4 4 4</td>
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<td>Identification of knowledge gaps 4 4 3 4 4 5 4 3 2 4 4 4 4 4 4</td>
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<td>Set of alternatives 2 4 4 4 3 4 4 4 4 4 4 4 4 4 4</td>
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<td>Cost/quality ratio</td>
<td>Cost-effectiveness of decision 4 4 3 2 4 2 3 3 4 4 4 4 2 4 4</td>
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<td>Robustness of decision 3 5 3 3 3 4 4 2 4 4 4 4 4 4 4</td>
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<td>Process progress</td>
<td>Sense of urgency 2 4 3 4 4 4 4 4 4 4 4 4 4 4 4</td>
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<td>Manageability of choices 4 3 3 4 4 4 4 4 4 4 4 4 4 4 4</td>
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<td>Decision time 4 4 3 4 4 2 4 2 4 2 2 2 3 3 3 2</td>
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### Timing and positioning

Most interviewees felt that the LCC study was initiated at the right time; the track selection issue was highly relevant in June 1999 and 2 months should have provided sufficient time to finish the study.

Most interviewees considered the study to be positioned correctly within the consortium, i.e. in the EPC Track working group; however, several interviewees mentioned that the importance of this decision should have been sufficient reason to have other parties better involved in the study. TS-int-8 and TS-int-13 pointed to the fact that the EPC Track group generally performed the analysis alone; this might have raised suspicion among those partners that were not represented in EPC Track. TS-int-1, TS-int-2 and TS-int-4 also felt that staff members from the M&R working group did not actively participate, which might have a negative effect on its credibility; they stressed that this situation was difficult to change.
Work approach and methods

Many interviewees explicitly stated that they appreciated the combination of LCC and failure mode effects analysis (FMEA) for feeding the choice process with quantitative data. TS-int-5, a member of EPC Track, described it as:

'The choice for a combined, quantitative analysis of risks and life-cycle costs, using the DSS, is crystal clear. It helped to test the sensitivities of our assumptions and to provide cost and availability forecasts for the decision makers'.

TS-int-10, who was a member of the top management, phrases it as:

'The life-cycle cost analysis, using your DSS, was an important instrument for the decision-making process within the consortium as a whole, but also for our engineering team'.

TS-int-3 expresses the view of more distant interviewees:

'I had the impression that the project team's work method was structured; it appeared to me as a logical approach, which assisted in evaluating cost and risk issues'.

Although many interviewees appeared to be reasonably satisfied with the quality of the methods used for data collection and interpretation, all were aware of the considerable problems in collecting trustworthy input data. It was acknowledged that gaining access to empirical data was always difficult under the conditions of the HSL tender and that 'best guess' assumptions were unavoidable (e.g. TS-int-13). Nevertheless, data collection could have been dealt with better according to some respondents. Firstly, it would have been better if all content experts had been part of the project team instead of being asked on an individual basis (or in pairs) for advice without further project responsibility. This was probably why different versions of the FMEA Incident Matrices followed quickly one after another, which made their status unclear (e.g. TS-int-1). In addition, one interviewee (TS-int-11) stated that 'the empirical performance records of the track systems from abroad should have been investigated more extensively'.

Shortcomings were also noticed in how the case studies coped with risks. Two interviewees, TS-int-4 and TS-int-13, mentioned that the performed analysis of operational risks for the different track systems was not sufficient; according to them, the consortium should have looked for an external advisor for ballastless track. TS-int-13 mentioned that the DSS had limited possibilities to analyse risks, TS-int-7 thought that too much time was lost while developing the DSS, and TS-int-10 felt that the calculation of train delay penalties did not sufficiently reflect reality. This made them doubt the exact outcomes, rather than the relative ranking of the solutions.

Several positive comments were received in relation to the flexibility of the decision support. TS-int-1 and TS-int-2 stated that the DSS immediately shows 'what it's all about in the financing of the track system' and that the DSS 'functioned at the right level of detail to help decision makers analyse different scenarios'. TS-int-3 noticed that the DSS helped to
underpin assumptions and contributed to accuracy: ‘if the results differed from what you expected, you had to do more research’. TS-int-12 stated:

'The DSS provides a to-the-point presentation of the most decisive cost contributors, comparable over time. You can analyse how much money is available for investment, if you eliminate for instance the need for tamping. Someone’s opinions can thus be tested: variables, that he or she thinks are of paramount importance, can be added in the models and assessed according to their relative impact'.

Alternatives studied

With the exception of one person (who was disappointed that asphalt track systems (ATD) had not been seriously considered) everyone was fairly content with the set of track systems studied during the Consultation Phase. However, most people mentioned that Direct Fastening (DF) was studied much too late and in too little detail, although it was selected as the consortium’s first choice. TS-int-7 mentioned that, as a result, its construction cost estimate had to be increased during the Tendering Phase.

DF was not included in the shortlist of solutions that had been specified before the LCC study commenced; some people provided explanations for this initial omission. According to TS-int-1 and TS-int-2, negative experiences with existing DF tracks in the Netherlands were the main reason for not including this system; the idea that DF could be an adequate option arose thanks to information from projects abroad and reports from the HSL Project Organisation. The belief that the concrete bed supporting the DF system could be well constructed in-situ (using a paver) was decisive. Statements from others confirm this explanation to some extent, but they perceived the role of the State to be crucial in choosing this solution (e.g. TS-int-5 and TS-int-9). TS-int-9 stated that ‘the Dutch State proposed Direct Fastening during the Schiphol meeting, because they were no longer sure that Embedded Rail (ERS) would be acceptable to the participating consortia’.

Impacts of the decision support

Everyone stressed the importance of the study for understanding the track selection problem by identifying decisive cost factors and their mutual relations. The DSS helped them to obtain more insight into the overall consequences of the track systems; combining initial capital and operating costs into one picture proved to be an eye-opener. They especially remember the bar charts with cost breakdowns and expected Performance Fees for each track system. TS-int-1 stressed that both the DSS development and its use contributed to a process of gathering knowledge; a serious remark, made by many, is that the DSS (re-)development took too much time.

Expanding the collective knowledge of the track design team had positive impacts on the decision-making process by raising issues for further research. This improved knowledge led to an increased awareness of some decisive track design issues, such as the connection between track system and substructure, and improving the robustness of the consortium’s track design to some extent (TS-int-1, TS-int-2, TS-int-6, TS-int-11). TS-int-6 stated that the study particularly helped to explain these issues to influential persons who were not familiar with track design. A number of explicit knowledge gaps were found, such as the identified
risks for slab track systems; for example, the question arose regarding if and how curves in the route would affect the maintenance needs of the Embedded Rails solution (TS-int-10). TS-int-13 believed that the fact that the LCC study provided explicit, traceable assumptions raised the confidence of the financial staff, while TS-int-9 said that it contributed to some staff simply not believing the Client’s comments.

However, opinions become more diffuse when considering the consequences in terms of relationships within the consortium. The analysis showed that differences between the track systems were smaller than the outcome of the balanced scorecard session had previously suggested, where Ballasted Track was selected as the obvious ‘winner’ and Shinkansen Track as the second-best solution. Some people reasoned that this improved the mutual understanding, while others thought the opposite. For example, while TS-int-2 stated that ‘we showed that the world is not that simple, which did not improve relationships’, TS-int-9 and TS-int-10 argued that the invalidation of some prejudices against track systems improved relationships. According to TS-int-8, the LCC study helped the EPC Track staff to function better as an integrated team: several skills were linked to each other and discussions could be better focused on the important aspects of the track choice. TS-int-10 phrased it as follows:

‘We could make choices more professionally. The message coming from the analysis, i.e. the track choice having more nuances, improved the relationships within the consortium’.

A few interviewees even saw counterproductive consequences of the analysis. TS-int-2 and TS-int-3 felt that people started to defend their opinions, something ‘which could not be avoided’ (TS-int-3). TS-int-6 mentioned that the DSS was used to stress the risks of particular track solutions and to present them as stronger ‘pro’ and ‘con’ arguments; this might have blocked innovative ideas. TS-int-7 thought that some ‘non-technicians’ focused too much on minor risks. On the contrary, TS-int-13 thought that ‘although the whole discussion became more objective under the given conditions, the risks of Embedded Rails were consciously underestimated’.

Considering the above, the question of how the study eventually influenced the choice made by the consortium was a difficult one for the interviewees, including those representing the consortium’s management. Although the LCC study made a couple of track systems more ‘discussable’, most interviewees stated that, in the end, strategic factors played a more decisive role. Nevertheless, according to TS-int-8, TS-int-10 and TS-int-12, at least one partner in the consortium was willing to reconsider its preferences, which helped to stop the ‘religious war between ballasted track and slab track’ (TS-int-8); this was a necessary condition for developing a sound opinion to be conveyed to the Client.

While TS-int-1 and TS-int-2 simply stated that they did not know how the final decision was taken, others believed that, for the consortium partners and the supporting banks, the HSL’s system design had to be entirely based on proven technology. TS-int-10 considered the choice for DF to be ‘a compromise between a low Net Present Value and the use of proven slab track technology’. According to TS-int-11, DF is the best slab track option to sell to the lenders, ‘since the technical structure is transparent and understandable’. TS-int-13 mentioned that ‘Direct Fastening is a readjustable system, up to settlements of 50 mm, which reduces the impact of some risks and fits the Client’s wishes; the choice is therefore partly
based on political reasons'. TS-int-3 mentioned the huge psychological barrier against Embedded Rails by those not familiar with track design.

Looking back, the interviewees expressed mixed feelings on the overall quality of the decision-making during the Consultation Phase. For example, TS-int-7 believed that the consortium had difficulties in coping with the risks that were allocated to the selected Infrastructure Provider: 'Attention was paid far too late to the real design and maintenance questions, since the analysis of these risks took considerable time'. However in the end, most interviewees had a moderately positive opinion of the choices made by the management. TS-int-1 considered both DF and ERS to be good options in terms of life-cycle costs, although: 'If we'd had the chance to build ERS, this would have been a revolution in the world of railways'. TS-int-2 felt that, in the end, ERS would have been a better solution for the HSL, if a risk-sharing regime could have been undertaken with the Client. TS-int-3 stated that both are good options for the State, but that 'ballasted track would have been a more logical choice, if the time horizon of the contract alone is considered'.

Finally, most interviewees considered that the LCC exercise was fairly successful, given the unstable conditions at that time. TS-int-6 mentioned that it was useful in shaping the 'mental models' of the people involved, although changing priorities within the consortium complicated the exercise. TS-int-8 expressed this as follows: 'A problem was that the objectives were changed several times, also by the Client, which is why significant effort was needed to keep the DSS functional and to validate all data adequately'. Finally, TS-int-12 puts the position of the LCC study in the entire process into perspective:

'The quality of the decision-making within the consortium was poor; I think that the combined risk and life-cycle cost analysis played a positive role: it was a step forward compared to intuitive reasoning. Statements and choices could be motivated better'.

Conclusions

The quantitative scores and the remarks made by the interviewees seem to provide a fairly consistent picture of the effectiveness of the LCC-based approach, i.e.:

- All interviewees appreciated the choice to feed the decision-making process with a quantitative analysis of risks and life-cycle costs, despite drawbacks such as time needed for model development, difficulties in risk quantification, and the lack of empirical data. More insight was gained into cost drivers in track design. Some prejudices were invalidated as a result, and some knowledge gaps (that needed to be dealt with) came to light.
- Apart from this being valuable for enriching the available information for the decision makers, the approach improved the manageability of the track selection process. All interviewees were of the opinion that EPC Track could motivate its choices better to other partners in the consortium. It also worked as a vehicle to focus discussion on key design issues, which improved EPC Track’s teamwork. The analysis showed more preselected solutions to be economically viable than was thought beforehand.
- Most controversy was found in the opinions on whether the analysis improved the mutual understanding between the partners, and this clearly indicated that many people had
already developed firm, divergent preferences for the HSL’s track design before the study commenced.

- The impact of the study on the track selection is a controversial topic. Overall commitment to the absolute outcomes was limited and two people even thought that it raised some suspicion as a few risks were consciously estimated too high or too low. Most interviewees tended to think that it did not (directly) lead to a more cost-effective solution. The analysis possibly played an indirect role in the track selection, but this is difficult to prove.

- The decision-making process during the Consultation Phase was acknowledged to be an unstable environment with considerable time pressure and regularly changing priorities, which hindered a well-grounded LCC-based approach. Nevertheless, the analysis increased the ‘sense of urgency’ among the stakeholders, which helped to move the decision-making process forward.

The conclusions versus the visible decision-making process

The findings from the interviews are generally well in line with the visible events in the analysis and decision-making (Sections 5.3 and 5.4). For example, the problems with the data collection and the analysis of risks are mentioned. The fact that the life-cycle cost analysis did not result in an unambiguous advice is mentioned as a reason why the interviewees cannot judge the influence of the analysis on the decision-making. Their position in the consortium was mentioned as another reason.

However, it is remarkable that many interviewees felt there was sufficient time for analysis, considering that time for seriously studying the Direct Fastening system was lacking. The interviewees seemed relatively moderate in their judgements of the final track selection, whereas the track type was heavily debated during the Consultation Phase; only two interviewees stated that, looking back, external (technical) advice for this decision should have been requested.

7.3 Perceived effectiveness in the HSL System Availability Case

This section evaluates the effectiveness of the LCC-based approach during the Tendering Phase (the process was previously known as ‘Optimisation’ – see Sections 5.5 and 5.6). Twelve people were interviewed 3 months after the case study ended. As Table 7.3 shows on the next page, this study was also highly valued for increasing the richness of the information available to the decision makers but, contrastingly, it also contributed to an increased commitment by stakeholders to the process and its outcomes. The table shows that high scores on these aspects were received from practically all interviewees; apparently, there is no doubt about the positive function of the provided decision support in that respect. On the other hand, it did not significantly improve basic attitudes and relationships, the manageability of choices, the set of alternatives, and the cost-effectiveness of the final decisions. Moreover, it was not perceived as speeding up the decision-making process, although it helped to raise the sense of urgency among stakeholders. One possible explanation is that the basic positions of the various parties did not need to change during this decision-making process, as there may not have been any underlying conflicts. Another explanation for the contrast between
increased commitment and unimproved relationships might be that the process concerned a ‘cooperation on the basis of necessity’. Finally, it is remarkable that the more negative scores were primarily received from the less involved staff, i.e. those who only participated a couple of times in the Optimisation Workshops or who viewed it from a distance. Explanations of the scores are pursued in the following section.

Table 7.3: HSL System Availability Case Scores (bold = assessed significantly positive)

<table>
<thead>
<tr>
<th>Aspects</th>
<th>Operational indicators</th>
<th>Interviewee</th>
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<tr>
<td></td>
<td>No.</td>
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<td></td>
<td>Role</td>
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<td></td>
<td>Involvement</td>
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<tr>
<td>Richness of inputs</td>
<td>Insight into situation/alternatives</td>
<td>3</td>
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<td></td>
<td>Identification of knowledge gaps</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Scope of alternatives</td>
<td></td>
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<tr>
<td>Cost/quality-ratio</td>
<td>Cost-effectiveness of decision</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Robustness of decision</td>
<td>3</td>
</tr>
<tr>
<td>Process legitimacy</td>
<td>Actors’ commitment</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Reformulation management goals</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Change in actors’ positions</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Relationships, mutual understanding</td>
<td>3</td>
</tr>
<tr>
<td>Process progress</td>
<td>Sense of urgency</td>
<td>4</td>
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<td></td>
<td>Manageability of choices</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Decision time</td>
<td>3</td>
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</table>

Timing and positioning

Half the interviewees considered the Optimisation to be initiated at the right time, whereas others felt that it started too late. For example, SA-int-9 argued that starting the Optimisation 6 weeks after receiving the Invitation to Tender (ITT) was appropriate: the various disciplines first had to make an initial design before the ‘optimisation’ exercise could commence. Others, especially SA-int-3, SA-int-7 and SA-int-10, thought that the consortium should have initiated the Optimisation earlier: sufficient time was available for the tender, but time had been wasted between September and November 1999 while waiting for the ITT. As a result, principle design questions were tackled too late. SA-int-3 mentioned that, theoretically, the process could have been finished 2 months earlier, in January instead of March, and that more time would then have been available for improving the tender documents. SA-int-7 even argued that this effort should already have been initiated in the Consultation Phase and that, as a consequence of the late start, the Optimisation was not well positioned within the consortium. On the other hand, SA-int-3 stated that ‘apparently the time was not yet right during the previous months; the availability issue did not get much priority and, worse, there was still a lot of ignorance of its importance’. SA-int-10 adds that the late availability of data on infrastructure failures complicated the information exchange with the potential lenders. SA-int-9 put the timing of the project into perspective:

‘I'll consider the fact that the designers of the EPC (engineering) working group started late with a good analysis as their own problem. The Steering Committee could not give much attention to the issue, since it was too busy setting up the Special Purpose Company and covering contractual risks’.
Practically everyone considered that the Optimisation was eventually well positioned within the consortium, but it first had to gain status and esteem within the organisation. SA-int-2 mentioned that System Availability was not at all well positioned within the consortium's organisational chart. SA-int-5 remembered that the first progress report showed an enormous level of performance penalties; this resulted in the engineering teams seriously revising their failure estimates and design plans. Since then, the Optimisation had gained esteem within the organisation. Both SA-int-5 and SA-int-8 mentioned that, in the end, the Optimisation had gained a strategic importance in motivating design and M&R choices towards the Client; it was included in the consortium's System Engineering Plan. SA-int-2, who was adviser to the management, stated:

"The Optimisation eventually succeeded in linking the EPC, the M&R working groups and the Special Purpose Company. It was well supported at the Steering Committee's Coordination Meeting, but did not have a formal position in the organisational chart. I think that the Optimisation role should not be underestimated. It was a good move to place it under the Financial Working Group, as this opened doors... The higher echelons had faith in it and it was a good way to prompt some people."

Work approach and methods
The decision to organise the study as a series of Optimisation Workshops, in which all engineering groups could participate in analysing possible performance improvements, was generally appreciated. Most interviewees valued the ability of the DSS to identify decisive performance killers, those types of failures that cause the highest level of penalties, and to relate all cost and performance contributions to the individual subsystems. For SA-int-8 it became clear that the direct costs of maintenance were less important than the initial investment and availability risks. SA-int-2 stated that the 'frustrating graphs' showing the performance penalties created a kind of useful competition between the groups. Several interviewees, such as SA-int-12, mentioned the ability to estimate the consequences of different failure frequencies immediately: 'It immediately showed where we would be heading'.

The interviewees expressed their confidence in the DSS, despite drawbacks that came to light during the Optimisation process; the majority were also satisfied with the introduction and use of the DSS by the project leaders in the workshops. However, some interviewees had minor objections. SA-int-1 and SA-int-5 thought that the DSS might have appeared to be a 'black box' for those that did not take part in the first session; they thought that more time should have been taken to explain its purpose to new entrants during later sessions. SA-int-3 argued that it was a step too far to present the absolute penalty levels to the participants; it might have been better to use a kind of neutral index to indicate the importance of the various failure categories. In SA-int-9's opinion, clustering failures into Incident Categories in the DSS was confusing: it was not possible to directly identify which failure types caused which penalty levels. SA-int-10 considered that the DSS concept could certainly be used in principle, but the calculation of penalty levels should have been based on the number of months with high penalty levels, instead of average availability levels. For several interviewees, such as SA-int-6, it was obvious that the DSS resulted in different forecasts than
the Monte Carlo simulation and that the outcomes had to be treated carefully. SA-int-5 felt that the project leaders were more concerned about the deviations in outcomes than the participants, which was perceived as a minor drawback of the DSS. According to SA-int-5, the estimations were used in a more relative manner, rather than an absolute way; he believed that both the DSS penalty forecasts and the chairman's constant grumbling about these forecasts helped to 'jolt' the engineers. SA-int-6 and SA-int-12 mentioned that it was important that the consortium did not rely on a single model, because financial interests were too high and models each have their own strengths and weaknesses; the DSS could certainly identify performance killers, but could not provide accurate penalty forecasts.

Interviewees signalled a number of important problems in the Optimisation. First of all, it took time to 'get the process going': the DSS development was not an obstacle this time, but involving all engineering disciplines in the process took considerable effort and time. SA-int-2 recalls the process as follows:

'We have gone through a process of awakening, in which the Optimisation was crucial. First, everybody became very cautious and conservative when they realised that they were responsible for the failure impacts. Then it became clear that a more serious and realistic estimation of the failures was needed in order to submit a bid to the Client that had a chance of being successful'.

Practically everyone noticed the varying quality of participation in the workshops and the absence of empirical data. A widely supported explanation is the lack of awareness among the engineering staff of the importance of the Performance Payment Regime (PPR). SA-int-10 and SA-int-12 mentioned another reason – the absence of individual responsibilities; the people who participated first were not the people who produced the data, which is why (a) they did not feel responsible and (b) could not directly agree with proposals from the Optimisation leaders. SA-int-10 suggested a third reason for the poor participation in the first sessions. Some EPC managers did not want to take any risk at first, which is why they wanted responsibility for a failure repair time only, whereas the Optimisation needed failure frequencies.

Although most interviewees were satisfied with the participation at the end of the process, the data collection problem persisted throughout the process. SA-int-2 summarises the essence of this problem well: 'The necessary information was mostly unavailable through a lack of historic M&R data, a lack of experience in high-speed operations, and the required use of innovative track and signalling technology'. A shortcoming, according to some (e.g. SA-int-5), was that a benchmarking study of the Belgian and French high-speed lines was initiated far too late. Others believed that the value of benchmarking was limited, due to the unique conditions on HSL South. Finally, several interviewees had experienced a number of other problems. SA-int-3 mentioned that the presentation of the high penalty levels might have 'killed' the creativity of the participants to some extent, since they felt they had to safeguard themselves from being held responsible. SA-int-5 mentioned that the workshops were often too chaotic, with considerable verbal confusion and the input from specific participants being openly doubted. SA-int-7 also considered the workshops to be too chaotic, and felt that the financial staff should have been more involved and that not all risks, such as
possession overruns, had been dealt with properly. He also argued that too much attention was paid to the choices in track technology and not to the choices in signalling. Finally, he thought that the importance of the Optimisation was undermined, since too many workshops were organised and the DSS output showed too many changes. SA-int-10 also argued that the continuing changes in data undermined the confidence of the financial staff:

'I wouldn't have minded if the engineers had stated that it's not possible to provide performance estimates for certain technical objects. However, they did not do that explicitly. Each time they promised to come up with better data, which is why the accuracy of all their data was doubted'.

Alternatives studied

Although several interviewees addressed practical examples of changed design choices and incident response strategies that were proposed and developed in the workshops, it proved difficult for the interviewees to reflect on the completeness and innovativeness of this set of alternatives. The scores for the indicators set of alternatives and selection of more cost-effective alternative in Table 7.3 clearly indicate that they had highly diverging views (standard deviations of almost 1 point) and this seems to be due to the fact that redesigning was mostly undertaken at the home base of the engineering groups.

The interviewees unanimously stated that the engineering groups improved their performance, but the exact measures taken and the additional costs were not clear to most of them; these measures were not well presented in the workshops. For example, SA-int-2 found it hard to judge whether the improved failure forecast resulted from consciously improved design and maintenance plans or simply improvements in the Incident Matrices, but he had confidence in the forecast. A similar remark comes from SA-int-7, who considered that the Optimisation was not a real ‘optimisation’ of costs and performance. Despite this comment and the serious objections from the previous paragraph, he greatly appreciated the Optimisation as a process that provides the right conditions to stimulate engineers into improving their plans.

It can be concluded that many interviewees had difficulty judging the outcomes of the Optimisation process in terms of improved design and M&R plans, but that they were sure that ‘system availability’ was clearly placed on each engineering group’s agenda. Most interviewees had confidence that this worked out well in improving designs.

Impacts of the decision support

Apart from raising awareness of the consequences of the PPR, the Optimisation workshops had significantly positive impacts on the quality of the availability forecast and the understanding and communication between the EPC and M&R groups. SA-int-12 stressed that it is difficult for engineering and maintenance people to speak the same language and that the Optimisation certainly helped to improve this situation. SA-int-6 stated that the workshops helped the engineers to deal with the questions from financial staff. SA-int-5, a risk analyst, stated:
‘We were in a deadlock in December: we received data that we did not trust. During the workshops the considerable impact of this input data became clear, which changed the attitudes of the disciplines’.

SA-int-7 summarised all other comments well in the following statement.

‘In my view the Optimisation served several goals, because it:
- made the disciplines aware of the impact of the performance payment regime;
- improved communication between the technical staff;
- led to all possible failure types being identified;
- brought the overlaps and gaps between the Incident Matrices of the different disciplines to the fore;
- pushed the disciplines to improve their subsystem design as much as possible, e.g. by designing in redundancy.’

The interviewees were also asked to look back on the final decisions and reflect on the overall quality of decision-making during the Tendering Phase; everyone except SA-int-10 gave the impression that they were reasonably satisfied with the bid that was finally submitted to the Client. Around half thought that this quality was the best that this consortium could reasonably have achieved. They considered the promised system performance to be feasible and the system design to be reasonably balanced, although it could have been better in terms of total costs. Remarkably, some interviewees expressed substantial confidence in the overall performance estimate, while they had doubts about the underlying Incident Matrices (e.g. SA-int-3 and SA-int-6). They seemed to reason that individual failure frequencies might turn out differently in reality, but that the combination of these expectations resulted in a realistic forecast.

Several interviewees had clear views on the quality of the consortium’s bid. SA-int-10 stated that the consortium did not understand the Client’s questions; a clear management philosophy should have been developed to avoid the risk of periods with high penalty costs. Too much focus was put on average failure frequencies. He added that, ideally the Optimisation should have been started earlier, but that the conditions were difficult to manage.

‘The problem with such a project organisation is that all partners need to have a sufficient share of power in the decision-making process. As a result, the process is difficult to steer. Apart from that, I would put the Optimisation first on the agenda for a new project of similar size and scope.’

SA-int-11 made a similar comment.

‘The risk analysis within the consortium was too scattered; from the start a small group of experts with authority should have been appointed to determine the required changes in the design and maintenance regime in order to reduce high risks.’

SA-int-3 felt that the trade-offs between investment, maintenance and disruptions could have been better: ‘In the end we did not supply a really integrated system design, although we had
a good overview of the decisive parameters. However, he puts this statement into perspective as follows: ‘Life-cycle costs were just one of the aspects we had to consider; we also had to develop a bid strategy’. SA-int-4 doubted whether an optimal solution was offered to the Client, since he thought that the track system choice was decisive in that and therefore Direct Fastening was not the best choice. SA-int-5 believed that the promised performance could be realised, but that it would require an alert incident recovery organisation and considerable preventive work; he was not sure whether all these costs had been included. In the opinion of SA-int-6, the analysis and optimisation of infrastructure performance had only just started: the question will return, for example, in the detailed design of the high-speed switches, since ‘the bid is still largely based on assumptions’. SA-int-8 and SA-int-9 considered that the bid was still on the conservative side and an upper limit for negotiations with the Client.

With regard to the Optimisation, a couple of interviewees thought that the consortium could have organised this differently and more effectively. SA-int-3, SA-int-5 and SA-int-11 felt that a small expert group, with authoritative power, could have completed the task more quickly; the Optimisation required participants to redo their homework several times and intensive plenary sessions were unavoidable. SA-int-12 shared this view; in his view, the Audit Committee has probably had a stronger impact:

‘The workshops and models of the Optimisation were important, but getting the right people is a matter of organisation. It is always difficult to get experts together’.

Conclusions

The quantitative scores and the remarks made by the interviewees provide a varied but clear picture of the perceived effects of the Optimisation process, i.e.:

- all interviewees were unequivocal in stressing that the Optimisation provided useful insights into the problem situation and knowledge gaps;
- it was helpful for mobilising available expertise among the engineering groups to reach a better system performance;
- because the redesign was mostly done within the engineering groups, interviewees had difficulty in judging the exact impact on cost-effectiveness and robustness;
- practically all interviewees recognised that communication between the EPC and M&R groups improved, particularly thanks to the last couple of workshops, although basic attitudes and relationships among consortium partners were not significantly influenced. A drawback, mentioned by some, was that the chaotic course of the workshops and the ‘volatility’ in the data affected the confidence of the financial staff, who mainly followed the process from a distance;
- creating commitment and overcoming the engineers’ ignorance of the performance payment regime took too much time. Some interviewees felt that a small expert group could have finished a review of the design plans quicker and with more authority, but that the Optimisation leaders were not to blame for this. A serious comment by one person was that the entire consortium should have taken a different approach to risk management, i.e. focusing on those failures with high impacts.

The conclusions versus the visible decision-making process
The interviewees’ responses are well in line with the process description (Sections 5.5 and 5.6). Many interviewees mention the fact that the analysis commenced rather late, considering the need to develop a cost-effective bid, and the limited initial commitment of the engineering teams to the process. Many interviewees also mention that the process was sometimes a ‘black box’, even for the process leaders, because the teams did not provide insight into their detailed design and maintenance plans.

7.4 Perceived effectiveness in the ProRail Track Renewal case

This section analyses the effectiveness of the LCC-based approach, as perceived by participants in a revision of ProRail’s track renewal (TR) practices during the LCM+ project (see Chapter 6). Sixteen people were interviewed 2-3 months after the case study. As Table 7.4 shows, this approach is highly valued for many types of effects; the interviewees saw a positive change in the basic positions and attitudes of all regional and central staff involved.

Table 7.4: ProRail Track Renewal Case scores (bold = assessed significantly positive)

<table>
<thead>
<tr>
<th>Aspects</th>
<th>Operational Indicators</th>
<th>Interviewee</th>
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<tbody>
<tr>
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<td>No. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16</td>
<td></td>
</tr>
<tr>
<td>Role</td>
<td>B E E E E E E E E E D E R E E D R D D</td>
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<tr>
<td>Involvement</td>
<td>H H H H L L H H L L M H M M M L L</td>
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<tr>
<td>Cost/quality-</td>
<td>Cost-effectiveness of decision</td>
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<tr>
<td>ratio</td>
<td>Robustness of decision</td>
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<tr>
<td>Process progress</td>
<td>Sense of urgency</td>
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<tr>
<td></td>
<td>Manageability of choices</td>
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<td></td>
<td>Decision time</td>
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However, opinions among the interviewees are rather diffuse and cautious with respect to the indicators sense of urgency, manageability, decision time and, most of all, reformulation of management goals, which has the lowest average and a standard deviation of 1 point. A number of highly involved experts gave particularly low scores and, as will be demonstrated later, these scores stem from a certain emotion and scepticism; apparently, there were fears that less involved staff would be unwilling to support the introduction of the agreed policy rules. Another possible explanation may be that there is a more general scepticism of the contingency of life-cycle-based strategies with existing procedures. A remarkable outcome is that many of the highly involved staff valued the approach for identifying gaps in existing knowledge, whereas less involved staff did not see this effect or were not able to give a judgement; possibly, the identified knowledge gaps had a more subtle nature, which made them less visible for more distant staff. The causes of these outcomes are pursued in the following section.
Timing and positioning

All interviewees agreed that the LCC study was initiated at the right time and several interviewees, such as TR-int-14, stressed that the project started at exactly the right time:

'First, we had to introduce life-cycle management as a method (i.e. the LCM-project); without LCM there would have been less support for this project. With LCM+ we showed that LCM is not only possible for individual investment decisions, but also for revising an entire technical policy. The name of the project was thus well chosen.'

TR-int-9 mentioned that:

'The planning groups (TEB) were only established in the regions in 1998, to enable the development and review of long-term M&R plans, separately from the daily work process. During the development and composition of the Track Renewal Forecast in 1999, there was no attention to life-cycle costs and the levelling of peak renewal volumes'.

Another convincing statement came from TR-int-6:

'The project was initiated at the right time. The LCM project had just paved the way for an LCC-based approach. People knew that their job could be done better, that several alternative methods were available and that a renewal peak had to be faced soon'.

All interviewees thought that sufficient time was available to perform the project, although TR-int-16 noticed that it had to compete with daily issues: ‘it had to be done between the soup and the main course’. TR-int-14 thought that the project timespan of 9 months was just right for sustaining enthusiasm among the participants.

All interviewees were satisfied with the positioning of the study within the Preservation Division, especially given the pilot-type character, the result of which remained to be seen; although, in some ways, it could have been better. TR-int-2 and TR-int-3 would have preferred to see more commitment by the top management. TR-int-6 thought that ‘the LCM+ project was not embedded at all within the organisation, but it had two strong supporters within the management, and that is sufficient to start such a project’. TR-int-16 felt that LCM+ was embedded fairly well, as:

'Many ProRail/RIB projects are organised centrally and do not involve the regions at all; this is particularly the case at NS and the Ministry of Transport. As a consequence, the results of these projects are not used in practice'.

TR-int-11 confirmed that the management had paid attention to LCM+:

'The regional directors were well informed, the project plan was consistently discussed within the Planning Board and the start of the LCM+ project was a formal decision taken by the Management Team'.
TR-int-9 is convinced that the project was sufficiently embedded up to the level of regional Planning Group managers. He and TR-int-10 seriously questioned whether ‘substance-driven arguments’ play any role at all at top management level: ‘Political reasons often determine decisions at that level. If they really support this approach, why don’t they initiate such projects for the other disciplines?’ TR-int-13 sees the LCM+ project as a solitary action by the Track discipline:

‘The other technical disciplines, i.e. civil, signalling and power supply, are completely different worlds; management should try to bring the work approaches of these disciplines closer together, which is not really the case. In a way it is understandable, since Track has a huge turnover’.58

TR-int-7 and TR-int-8 suggested that embedding LCM+ within the organisation still has to start, expressing what many tend to think (see the end of this section):

‘Much depends on the people involved, who each have priorities of their own. Although LCM+ was better supported than usual, management should recognise that they have to provide resources, especially work time, for carrying out such a project and to guarantee its implementation. The main risk for LCM+ is that everybody starts to interpret the rules differently’.

TR-int-15 and TR-int-16 mentioned two possible strategic reasons for explaining why the project was well embedded. TR-int-15 argued for increasing the necessity of the forecasted TR peak. TR-int-16 added that LCM+ was seen as a way to develop a usable policy instrument: ‘We feel that, for years now, infrastructure quality has been insufficient to accommodate current transport volumes. With life-cycle costs analyses, we might underpin maintenance needs better and inform the Ministry of Transport in time’.

**Work approach and methods**

All interviewees appreciated the approach taken in the LCM+ project, including the analytic support provided in the pilots and plenary discussions. TR-int-1 deemed this step-by-step approach to be clear from the start, although it was not crystal clear how it would end. His remarks summarise the views of practically all interviewees:

‘At the start, the Group Decision Room (GDR) created enthusiasm and an open attitude; I was surprised that the participants could come up with so many different solutions. This is attributable to the approach and the ambiance; they could look at their daily work from a distance. The pilots also worked out very well, thanks to adequate support and feedback to the participants. This was the strength of the project: information from the participants was well received and used. The presentation of the results with LCCP helped and triggered people to provide accurate data and improve their assumptions. I have no reason to doubt the results of the pilots and the overall findings of LCM+; of course, it may be that policy-makers consider other, political, aspects in their choices. Cooperation between the regions

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58 Others, such as TR-int-13, expect that life-cycle cost analysis will be less beneficial for the other disciplines, because the maintenance and renewal is less focused on condition degradation.
and central staff was better than usual, since the "hats problem" did not occur".\footnote{The 'hats problem' refers to the fact that staff members have to consider national and regional interests at the same time, i.e. developing national plans, while representing their region's interests.}

A number of additional remarks, mostly from regional experts, are added to complete the above impression. TR-int-2 and TR-int-3 considered the presentation of the results with LCCP to be helpful for improving input data, since 'strange' outcomes could be traced. TR-int-4 and TR-int-5 stated that the presence of a central analyst helped in encouraging the regional teams. TR-int-6 agreed, and added that the approach created a number of important ambassadors in the regions to propagate the LCM+ approach. TR-int-8, who was initially afraid that the project would mostly be a computer exercise, was pleased with the project course:

'The functional, supportive DSS use and the motivating discussions created more commitment. The teamwork was good. The final session was also a success; it actually reanimated a ruling Track Renewal policy'.

TR-int-8 also mentioned that this project was different from others, since the members of the Planning Groups used to meet only once a year, while in this project the planners for track M&R met almost every month. For TR-int-11, it was an exemplary project, since different M&R methods were systematically compared according to their costs per unit of product:

'It was approached more fundamentally than I had expected. The number of solutions and the "transformation" of the results into specific policy rules exceeded my expectations. The GDR session and the positive feedback afterwards, created a collective feeling, which made the pilots so successful. The openness, which normally makes people vulnerable, was exceptional. Finally, everybody could share in the discussions during the Policy Workshop and employ his/her professional skills; this is rarely the case nowadays'.

The LCM+ project helped to confirm a number of existing and new M&R practices with economic calculations. TR-int-13 noted that it first took some time to find a joint calculation base for the costs and productivity rates, because project scopes were jumbled in the estimates: 'In the first phase, we were comparing apples with pears'.

Everyone expressed their confidence in the final estimations of LCM+ and, with the exception of a couple of interviewees with some small doubts, were highly satisfied with the input data used. Most interviewees simply stated that they had no reason to doubt the outcomes, as they corresponded well to known figures. Several interviewees felt that, in reality, outcomes may deviate from the estimations, but that the ranking of the M&R alternatives was trustworthy and based on state-of-the-art knowledge. TR-int-13 had doubted certain estimates, particularly regarding minor maintenance:

'I doubt whether some predicted maintenance reductions come true, since they are part of the outsourced work load; moreover, you also depend on
other ProRail/RIB departments, which do not always implement projects according to your plans'.

TR-int-12 doubted the relevance of the forecasted cost saving by LCM+:

'This saving is based on the 20-year Track Renewal Forecast, which includes average life expectancies and has not been updated during the last 3 years. Also, what is the value of a 10% reduction, compared to the expenditures resulting from the policy to remove all Nefit track from the network?'

Everyone was pleased with the course of the process. They felt that they could influence the process and felt fully part of the team. For TR-int-15, LCM+ showed that significant results are feasible with limited resources, while it was clear to TR-int-16 that the right people were involved.

A number of minor comments regarding the process management were made. For TR-int-2, TR-int-3, TR-int-12 and TR-int-13, the presentation of the results was very useful, but sometimes resulted in an information overload. TR-int-2 stated: 'The amount of information was sometimes too ambitious for the ProRail/RIB culture. It takes time for ideas to take root in this organisation'. TR-int-12 and TR-int-13 put this into perspective as follows: 'As engineers, we are also ambitious in that respect. Once we see results, we want to know where they come from; in other words, we want to know all the details'. Finally, TR-int-7 and TR-int-8 would have preferred to discuss in even more detail the validity of the assumptions used in the pilots, but they admitted that this might have undermined the open attitude of other participants.

Alternatives studied
Most people thought that the list of alternatives for track M&R used in this project was fairly complete, although the project focused on those solutions that could realise short-term savings ('quick wins'). TR-int-1 also mentioned that the project’s starting point was to use a track system in a good-quality ballast bed. TR-int-9 particularly ascribed the completeness of the set of alternatives to the first brainstorm session (the GDR). TR-int-12 commented that the renewal of sleepers and ballast on side tracks only was not included in the pilots. For him and TR-int-13, the pilots showed that more solutions exist than planners in a single region have become familiar with. TR-int-10, who participated in the last 2 months of the project, had difficulty in immediately comprehending all alternative work methods developed during LCM+: 'I was surprised that so much work had already been done on the project'.

However, several interviewees felt that there are even more opportunities for new policy rules. TR-int-7 referred to a couple of new solutions that became available after the project had ended (see Section 6.7; according to him, the discussed milling solution might be applicable to 80% of all Nefit tracks). He did not see this as a shortcoming of the project, but sees LCM+ rather as 'an ongoing process, since new work methods and systems will continue to become available'. But both TR-int-7 and TR-int-10 added that the promises of preventive grinding strategies in improving rail and track life should now be studied. TR-int-15 posed that a range of more refined M&R measures can still be elaborated, e.g. by analysing the life
cycle of a switch on a micro level. TR-int-16 mentioned that the logistical processes for the contractor had not yet been studied in detail.

**Impacts of the decision support**

Asked about the general impacts of LCM+, most interviewees were convinced that ProRail’s TR policy had become more flexible and tuned to local conditions. TR-int-6 argued:

‘Too many people within the organisation are still thinking too much on an operational level, which is why impacts on the entire railway system are not seen. LCC can help to improve this and can also be an instrumental in breaking the walls between the Construction and Preservation Divisions’.

TR-int-9 and TR-int-10 put it as follows:

‘The policy was lifted to a higher level. With LCM+ we analysed the residual track life in combination with all maintenance options and operational requirements; this resulted in an instrument to plan renewals earlier or later’.

TR-int-11 stated that, in the past, the ‘policy level’ did not stimulate track M&R planners to review different solutions. TR-int-14 considered that good ideas are now taken seriously on a national level; for example, reusing materials is no longer regarded as someone’s personal hobby. For TR-int-12, the robustness of the technical TR policy can now be better managed in relation to the political and operational setting. TR-int-13 argued that a particular alternative is harder for decision makers to refuse if it is based on such a thorough analysis. TR-int-14 was convinced that the new, LCM+ based policy will result in lower expenditures and a better performance, but added:

‘This certainly does not mean that we will be refunding money to the government; we would rather use it to utilise the available budget better and to deal with backlogs in M&R!’

TR-int-6 summarised the remaining views:

‘I was surprised to learn that there is often a possibility to choose between two alternatives that are similar in terms of life-cycle costs. It means that you can choose the one that best fits the available budget and possessions; as a company, it means that you can level out renewal peaks over the years. Finally, LCM+ also points out that particular alternatives should no longer be used’.

Despite some uncertainties, most interviewees thought the LCM+ rules were fairly robust for the next few years, at least from a technical point of view. TR-int-1 did not see any obstacles to practicing LCM+ in projects based on scarce budgets: ‘We can always choose the least damaging prioritisation, given the actual cash flow’. Only TR-int-15 questioned whether the instant reuse approach would be usable in that case: projects will then be rescheduled, which complicates a combined implementation.
Nevertheless, most interviewees added that a periodic review and updating of the input data is necessary in order to preserve the reality and accuracy of LCM+ for the future. A number of interviewees suggested that the LCM+ implementation might benefit from an independent screening of the assumptions or second opinions, e.g. in cooperation with universities, ProRail’s contractors and other ProRail departments (TR-int-14). TR-int-7 and TR-int-8 noted that new pilots should also be undertaken to continue developing ‘life-cycle knowledge’ at ProRail. TR-int-15 stated that the input data is mostly based on expert opinions, ‘stored in the brains of our maintenance staff’. For him, it is now time to further improve the empirical decision-making base.

All responses stressed that the project clearly helped in improving relationships between the regions, which also favoured the sharing of knowledge. TR-int-2 stressed that sharing knowledge between the regions is not standard practice, which is why LCM+ was so important:

'Sharing knowledge is usually carried out by contractors rather than us. If a contractor's regional office has developed a smart practice, then the other offices also want to know about it; but within ProRail the regions work more independently from each other'.

A remarkable finding in this respect was the fact that several regional experts pointed to the application of LCM+ in other 2002 production plan projects, apart from those that were part of the pilots. The examples they mentioned clearly show that cross-pollination of ideas between the regions had already taken on a specific shape, although the official 'rollout' of LCM+ was planned for the 2003 production plan. TR-int-4 and TR-int-5 mentioned the Apeldoorn-Amersfoort project, a large corridor-based renewal, where all rails will be stored and used in another project. TR-int-4 added:

'LCM+ changed my view on reusing materials (cascading). My attitude was less positive at the start because it requires considerable organisation and logistic efforts. If we had time to perform this type of optimisation better, we could save more money'.

TR-int-7 and TR-int-8 also mentioned a project in which they would use LCM+:

'We will take a main-line switch from the town of Etten-Leur and reuse it on a side track in the village of Veghel. We will really try to apply this reuse approach, although we have fewer opportunities than the RIMcity Regions'.

TR-int-12 and TR-int-13 referred to a new project on the Hofplein line, between Rotterdam and The Hague, in which they intend to apply the lighter track design.

Most interviewees expect that a thorough application of LCM+ requires more time and effort, since a larger set of solutions has to be given serious consideration. TR-int-2 and TR-int-3 notice, for example:

'In some cases, TR decisions are still mainly triggered by theoretical lifespans instead of the local situation. This is because condition-based renewal is more demanding for the organisation'.
Several others, such as TR-int-15, see fewer obstacles to using LCM+ in the production planning: ‘On one hand such an analysis is more complicated, but on the other hand, the agreed rules probably make discussions more manageable’. TR-int-2 adds that LCM+ provides more opportunities for a more controlled TR process than project-based LCC studies, as required in ProRail:

‘If, for example, you replace a group of switches, there are always going to be mixtures of younger and older switches. Using LCM+, it is possible that a number of switches can have a second life at other locations. However, if I want to renew something in a project, I can always come up with a favourable life-cycle cost analysis: nobody would question my assumptions’.

Practically all interviewees argue that the opportunity for implementing the full potential of LCM+ largely depends on the sense of urgency and commitment within the ProRail/RIB management. They all stressed that LCM+ still has to be firmly rooted in the organisation. As TR-int-16, one of the managers, put it: ‘At the moment, a sufficient dose of maintenance is needed for LCM+; we should persevere at implementing its results’. TR-int-2 and TR-int-3 feared that people would withdraw to their former positions under influence of others, such as the Regional Directors and the Execution Group managers. TR-int-8 mentioned something similar:

‘I have the idea that the region where the particular pilot was performed is still its biggest supporter. Application of the LCM+ rules should therefore be stimulated throughout the country’.

A range of practical suggestions were received from the interviewees regarding implementing LCM+ in daily processes; all favoured a similar application of LCM+ across the regions and could therefore accept increased central coordination, but views on the precise implementation methods differed (see also Section 7.5). Many interviewees recommended that action should be taken to overcome obstacles, such as the time-consuming procedure for claiming possessions, the fact that data is scattered over different parts of ProRail and is therefore not accessible, and the instabilities in the budgeting process, which urges regions to compete. A few mentioned that cooperation by other stakeholders, such as contractors and transport operators, should also be arranged (e.g. TR-int-16).

Most interviewees balanced between cautious optimism and ‘light’ scepticism when reflecting on the prospects for LCM+ implementation, particularly the awareness of the TR problems at management level. They thought that policy changes are only stated ‘verbally’ and not really put on the personal agenda. TR-int-2 referred to a well-known Dutch expression: ‘First seeing, then believing’. He states:

‘Despite all good intentions, regions are still budget-driven; instead of making efforts to reuse an existing switch, it is better to request a new one, since negotiations generally follow the “cheese-slicer method” (i.e. if a budget cut is necessary, it is equally applied to all regional budgets’.

TR-int-3 adds:
‘Everybody says that life-cycle costs are very important, but, in practice, many decisions are overruled because other interests are at stake. Think about the imposed removal of Nefit or the installation of concrete sleepers because they reduce noise by a few decibels’.

TR-int-4 and TR-int-5 stress that the implementation of LCM+ is threatened by the fact that the ‘scope’, i.e. contents of TR projects, is not well controlled.

‘The production plan should be centrally coordinated, if it is meant as a steering instrument. Now, the plan is transferred to others, who simply carry them out. They modify the plans without giving notice and asking feedback.’

TR-int-6 questioned whether everybody would be willing to make the effort: ‘You get support from certain people because they see that it is important. However, they will not do it themselves without incentives and means’. TR-int-14 was of the opinion that not everybody had woken up yet: ‘Maybe we should have shown the Management Team what could have been saved with LCM+ in the 2002 production plan’. TR-int-11 expressed his feelings as follows:

‘The current production plan comprises only project budgets: you are judged on spending the largest budget, not on the accomplished cost-effectiveness. Management should ask the right questions to bring about a cultural change; insight should be provided into costs per unit of product. Benchmarking between the regions can initiate a learning process. Regional autonomy is not a problem, but monitoring and steering their performance is a prerequisite’.

Finally, TR-int-16 places these threats to the success of LCM+ in the context of the entire organisation:

‘Public projects are financed on a cash basis, and ProRail is therefore a budget-driven organisation, but is nevertheless judged on its output. From a business economics point of view this is killing for LCM and incorrect practice. There is considerable reluctance, because if you refund money once then you will never get it back’.

Conclusions

From the quantitative assessment and the above discussion of opinions, it became clear that firm conclusions are possible regarding the success of the LCM+ project.

- The timing of the project was considered excellent. The ‘LCM project’ had paved the way for a life-cycle costing application and the expected peak volume in track renewal increased the urgency for developing a sound renewal policy.
- There was general appreciation of the approach taken, the assistance given and the process management provided by this author and two ProRail staff. In contrast to other studies, everyone felt that considerable effort had been made to involve the regions right from the start. The project steps were perceived as logical and helpful in triggering serious debates;
the project setting made it possible for regional experts to view their work from a distance and entirely from a ‘long-term impact’ perspective.

- The availability of a central analyst (i.e. this author), who prepared meetings and visited the regions to ask critical questions and assist in the pilots, functioned as a crucial vehicle in pushing progress forward.
- Plenary sessions, such as the GDR brainstorm session and the Policy Workshop, were often mentioned as success factors, since they created enthusiasm and helped to translate ideas into specific M&R solutions and policy rules.
- The regional pilots helped to analyse the generated solutions in a practical and urgent setting, which made the analysis and discussions highly realistic; the pilots also helped in creating ‘ambassadors’ of the LCM+ approach in the regions.
- The supportive background role played by the LCCP was appreciated during the data collection and validation process, as well as in ‘extrapolating’ outcomes from the pilots.
- Everyone considered the results and recommendations to be trustworthy and were convinced that a fairly robust policy resulted, which gives more consideration to local conditions; though a couple of interviewees had minor doubts about specific outcomes.
- All participants stated that the policy rules must have commitment from all regional planners and track specialists, and most of the interviewees strongly believed that people’s basic attitudes have changed. Examples of cross-pollination of ideas were provided.
- Thanks to the study, the regional staff changed their views on methods used by colleagues in other regions, which is why everyone favoured the continuation of the LCM+ Expert Panel in a Track-wide Board. They also favoured a coordinated implementation of LCM+, as it would be important that the LCM+ rules are applied similarly across the various regions; many interviewees would accept more central coordination, although ideas for changes were not entirely uniform.

The aforementioned factors easily explain the high scores for the decision support provided, as were depicted in Table 7.4. The table and discussion also expressed the low expectancies related to improving the manageability of the TR planning process and the firmness of management support. This shows a different picture.

- The majority of the experts were only moderately optimistic about the continued effectiveness of LCM+, which is remarkable when everyone fully accepts the results. In that respect, there is a gap between interviewed experts and managers; the experts tend to be more pessimistic about the future of LCM+ in planning renewals.
- The main concern was whether changes stated ‘verbally’ would really be implemented. A threat could be that (over time) the regional experts would return to their former attitudes and practices, if others in their region do not support or stimulate the application of LCM+. Several interviewees explicitly stressed that a cultural change is required; regional autonomy does not have to be a problem, but courage is needed to draw everyone’s attention to best practice as well as to mistakes, in order to learn from them.

Based on the implementation results of LCM+, information is available to verify the expectations expressed during the interviews. It was shown that the implementation was indeed hindered by the lack of commitment, which made the LCM+ core team decide to leave the application of LCM+ more or less as a task for the regions (see Chapter 6). In August
2003, interviewees were asked for their current view on LCM+. Several said that they use LCM+ in their region and considered the rules to be very helpful; TR-int-2 confirmed that they had already made substantial savings. Practically all responses stressed that courage is needed in applying LCM+. They admit that the current use of LCM+ is too limited. A couple of people expect that the audit, which was organised in 2003, would provide a new stimulus for improving the planning process. TR-int-2 argues that coaching and demonstrating good LCM+ examples is necessary to stimulate regional planners.

The conclusions versus the visible decision-making process

The observations of the interviewees are well in line with the process description in Chapter 6. In 2003, after the implementation of LCM+, several interviewees proved to have moderated their expectations; this seems well in line with the developments since 2001. The expectations on the robustness of a couple of policy rules seemed to have been overestimated. Finally, it is remarkable that most interviewees stress that a complete list of alternatives was studied, whereas the ‘milling solution’ for Nefit track emerged later (see Section 6.7).

7.5 Discussion and conclusion: effectiveness of the LCC-based approach

This section integrates the findings on the effects of LCC-based support during the three case studies, as presented in Sections 7.2 to 7.4. Table 7.5 provides a concise overview of the case studies (see next page). The top part of the table contains the received assessment of the success indicators. Success indicators shown in bold were assessed as significantly positive by the interviewees. The number of positive responses, out of the total received scores, has been added in brackets for each indicator.

The participants in the decision-making processes for all three case studies valued the LCC-based support for providing a new, quantitative type of data on costs and performance. Assumptions by designers and maintenance experts became transparent, which allowed replicable discussions that focused on the decisive cost drivers. This is reflected in the positive scores for the indicators ‘insight into the problem situation and alternative solutions’ and ‘identification of knowledge gaps’ in Table 7.5 (see page 210). However, most interviewees thought that the LCC support did not contribute to a reduction in decision time.

Despite the LCC-based support providing desirable information, judgements on the impact of this information on the decision-making process differed significantly from case to case. In the first case, the decision support provided only brought about an increased ‘sense of urgency’ among decision makers and a better manageability of the study of track systems by the EPC Track group. Apparently it did not really influence the final choice or its expected cost-effectiveness, nor did it significantly improve the interactions between actors in the process. It would appear that basic attitudes and preferences could not be reframed into a shared view on the solution to be chosen; clear commitment to the process was limited to the EPC Track group. Contrastingly, in the second case study, the decision support provided did contribute to more commitment and a reframing of opinions. The engineering teams committed themselves to providing performance estimates, although apparently the decision support could not really control the dynamics of this process. Also in this case, the
interviewees were mostly undecided on whether it eventually led to better design and maintenance strategies. In the last case study, it was clearly possible to create commitment to a policy direction, where everyone believed it would lead to better and more legitimate decisions in terms of life-cycle costs. Some participants reconsidered earlier standpoints and the data gathered provided sufficient grip for a policy change. This case showed that LCC-based support can realise more than just an improved information basis for decision-making. It can have important process effects, i.e. creating commitment to new policy directions. Nevertheless, even in this case, participants were not sure of sustained support for the outcomes within the organisation.

The effects found in the case studies indicate that LCC-based decision support appears to have important, positive impacts in environments where there is lack of data and uncertain commitment. This is a first confirmation of the expectations of Chapters 3 and 4. Remarkably, the findings seem to suggest a clear order in the feasibility of the various effects of LCC-based support. The following list presents the functions of LCC-based support, as recognised by the participants, from the easiest to the most difficult to achieve.

1. **Identifying decisive cost drivers and performance killers.** Even developing rough life-cycle cost models can stimulate a review of assumptions. A first set of input data (e.g. a reference design or maintenance solution) can be used to identify key cost drivers and performance killers. The relevance and sensitivity of input factors, as proposed by design or maintenance staff, can be tested by simulating various operational conditions (scenarios).

2. **Validating and invalidating ideas on system-wide decision impacts.** If verifiable data becomes available, then system-wide impacts can be traced easily. Many interviewees viewed the produced cost breakdown charts as eye-openers, because they crossed traditional organisational boundaries. The analysis can thus increase the sense of urgency for a life-cycle approach to decision-making.

3. **Assessing the effectiveness of a broad range of design and M&R solutions.** In an open atmosphere, this exercise stimulates an exchange of ideas among designers and maintainers and the assessment of a broad range of design and preservation strategies. The last case study indicated that a fair, trustworthy ranking of decision alternatives, as perceived by the participants, is feasible.

4. **Changing basic attitudes and mutual understanding.** Under certain conditions those involved are willing to reconsider earlier standpoints, which improves the mutual understanding between the actors involved. For example, experts in the LCM+ project accepted solutions that were previously considered as ‘someone’s hobby’.

5. **Creating commitment to new design or M&R strategies.** Under certain conditions the LCC-based approach proves able to create commitment by stakeholders to changes in design and M&R strategies, as the ProRail/RIB case indicates. Although it is too early for firm conclusions, it seems fair to say that sustainability of this success is not guaranteed if there is insufficient willingness or ‘focus’ within the organisation to systematically analyse the system-wide cost impacts of decisions. This did seem to be the case within ProRail/RIB during the period immediately following the LCM+ project.
Table 7.5: Main outcomes and features of the case studies

<table>
<thead>
<tr>
<th>Richness of decision inputs</th>
<th>HSL Track Selection</th>
<th>HSL System Availability</th>
<th>ProRail Track Renewal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insitit situation (10/13)</td>
<td>Insight situation (9/11)</td>
<td>Insight situation (16/16)</td>
<td></td>
</tr>
<tr>
<td>Knowledge gaps (9/12)</td>
<td>Knowledge gaps (9/11)</td>
<td>Knowledge gaps (9/13)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quality of decisions</th>
<th>HSL Track Selection</th>
<th>HSL System Availability</th>
<th>ProRail Track Renewal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robustness (8/13)</td>
<td>Robustness (7/11)</td>
<td>Robustness (11/15)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Legitimacy of process and decisions</th>
<th>HSL Track Selection</th>
<th>HSL System Availability</th>
<th>ProRail Track Renewal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formulation goals (6/11)</td>
<td>Formulation goals (8/11)</td>
<td>Formulation goals (9/16)</td>
<td></td>
</tr>
<tr>
<td>Commitment (7/12)</td>
<td>Commitment (10/11)</td>
<td>Commitment (10/16)</td>
<td></td>
</tr>
<tr>
<td>Actors' positions (5/11)</td>
<td>Actors' positions (5/10)</td>
<td>Actors' positions (9/15)</td>
<td></td>
</tr>
<tr>
<td>Relationships (7/11)</td>
<td>Relationships (7/11)</td>
<td>Relationships (13/15)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time and efforts needed</th>
<th>HSL Track Selection</th>
<th>HSL System Availability</th>
<th>ProRail Track Renewal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sense of urgency (10/12)</td>
<td>Sense of urgency (10/11)</td>
<td>Sense of urgency (8/16)</td>
<td></td>
</tr>
<tr>
<td>Manageability (11/13)</td>
<td>Manageability (7/11)</td>
<td>Manageability (5/15)</td>
<td></td>
</tr>
<tr>
<td>Decision time (5/13)</td>
<td>Decision time (2/11)</td>
<td>Decision time (6/16)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Main functions/Strengths</th>
<th>HSL Track Selection</th>
<th>HSL System Availability</th>
<th>ProRail Track Renewal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identification of cost drivers and types of operational risks</td>
<td>- Improved, robust policy - Attitudes changed - Broad set of alternatives - Exchange ideas Regions - Policy becomes less rigid - Commitment to policy - Trusted analyst</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Identification of performance killers - Improved incident data - Mobilised commitment - Better communication - Trigger creative thinking</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>- No ‘winner’ among the track systems appointed - No strong commitment - Unclear role in decision - Subjective risk analysis</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Initiator</th>
<th>Track Engineering Group</th>
<th>Financial Group</th>
<th>Deputy Director M&amp;R</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Subsystems</th>
<th>HSL Track Selection</th>
<th>HSL System Availability</th>
<th>ProRail Track Renewal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track excluding switches</td>
<td>Track, power, signalling</td>
<td>Track, signalling</td>
<td></td>
</tr>
<tr>
<td>- Many staff changes - Race against time - Low initial priority of System Availability</td>
<td></td>
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<tr>
<td>- Ambiguous interest Regions in Production Plan - Project is given independent position</td>
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<table>
<thead>
<tr>
<th>Context</th>
<th>HSL Track Selection</th>
<th>HSL System Availability</th>
<th>ProRail Track Renewal</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Small analysis team - Ad-hoc expert consultation - Analyst in DSS chauffeur</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Large plenary sessions of engineers and managers - Analyst also role in process management</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Small core team with full-time analyst - Regions in Expert Panel, develop new solutions</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Study set-up</th>
<th>HSL Track Selection</th>
<th>HSL System Availability</th>
<th>ProRail Track Renewal</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Quantitative approach highly appreciated - M&amp;R group and other parties not well involved</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Approach with workshops appreciated - All stakeholders became actively involved</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>- Adequate management support and leadership - Perfect timing after introduction of LCM</td>
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<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Embeddedness</th>
<th>HSL Track Selection</th>
<th>HSL System Availability</th>
<th>ProRail Track Renewal</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Much time was spent in developing track design</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Many time was needed to involve engineers</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>- Empirical base uncertain - Contractors and TOCs not directly involved</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Engineering disciplines not eager to agree on performance levels - Unprecedented renewal volumes to be faced</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Underpaid funding needs</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Time available</th>
<th>HSL Track Selection</th>
<th>HSL System Availability</th>
<th>ProRail Track Renewal</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Thin empirical base - Confusing expert advice</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Empirical base unclear - Experts were found late</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Excessive emphasis on speed - Excessive emphasis on cost</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Data quality</th>
<th>HSL Track Selection</th>
<th>HSL System Availability</th>
<th>ProRail Track Renewal</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Varying preferences between partners - Opinion of the Client</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Engineering disciplines not eager to agree on performance levels</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Unprecedented renewal volumes to be faced - Underpaid funding needs</td>
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</tbody>
</table>
The causality in the order of the above cannot be validated, but it seems to fit well with models in the literature on innovation and change processes [see Talvitie, 1995 and Wallsgrove, 2003] and the literature discussed in Chapter 4 (see Table 7.6).

Table 7.6: LCC as a process of change and acceptance

<table>
<thead>
<tr>
<th>LCC functions</th>
<th>General models on acceptance and change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Identifying cost drivers/performance killers</td>
<td>1) Recognise problem</td>
</tr>
<tr>
<td>2) (In)validating ideas on decision impacts</td>
<td>2) Share problem definition and goals</td>
</tr>
<tr>
<td>3) Assessing and selecting design/M&amp;R solutions on the basis of cost-effectiveness</td>
<td>3) Share instrumental preferences</td>
</tr>
<tr>
<td>4) Changing attitudes/mutual understanding</td>
<td>4) Accept selected instruments</td>
</tr>
<tr>
<td>5) Creating durable commitment</td>
<td>5) Apply</td>
</tr>
</tbody>
</table>

In addition to this set of feasible functions, it also proves possible to list a set of conditions that appear to stimulate, or restrict, the effectiveness of LCC-based support, according to the participants in the decision-making. Interviewees mentioned two causes for explaining why the information generated by the LCC study did not lead to significant changes in the decision-making process. Firstly, the set of quantitative data is too 'weak' and surrounded by too much uncertainty. The problem of quantifying several major risks of the various HSL track design solutions was an example. Secondly, stakeholders were not fully involved in the study. Again, the first case study serves as an example, and proved that supporters for any of the analysed solutions could be found within the consortium, which had already developed strong preferences in advance. The study, performed by one of the parties, was thus placed in a relatively political setting, which caused doubts or even suspicion by the others. A basic commitment in advance (by the parties involved in the decision-making) seems therefore a necessary condition for such highly debated decisions. It may be that the absence of commitment leads to a vicious circle of reduced trust, cooperation and data reliability. The reason is that a 'thin' empirical database requires the cooperation of a whole range of actors to collect a set of acceptable input data. For example, the HSL interviews showed that certain people, who did not actively participate in the study, had developed a relatively negative opinion regarding the quality of the outcomes, because of a signalled volatility in reported outcomes or because they suspected some risks to be consciously underestimated (or overestimated). All in all, the following list of conditions can stimulate or hamper the success of LCC.

- 'Political/management pressure'
  Interviewees in all cases mentioned the strength of top management support to be a crucial factor for (continued) success. It can apparently make or break a large part of the success of the 'LCC exercise'. It can create a sense of urgency, which can work out positively.

- Character of decision arena
  In all case studies, different groups were present, with different stakes, concerns or ideas. In both the HSL and ProRail cases, the LCC study had to compete with other important issues, but the sense of urgency among the participants for the studies seemed to be larger in the HSL environment, because all important design and M&R choices still had to be made. On the other hand, the potential impact of LCC was reduced by the absence of empirical data. At ProRail, teams from each region participated, having already developed
their own practices and principles; relatively many participants doubted the commitment of the executive staff to support improvements in the maintenance process.

- Availability of data
  The studies for the Madrid Metro extensions (see Appendix D) and the HSL demonstrate that the quality and availability of underlying data can vary significantly for identical types of decisions. Both concerned the selection of a track system but, in the first case, 20 years of track M&R data were more or less available, whereas for the HSL, empirical data was hard to obtain or use. The participants felt that this increased the risks and the difficulty of the analysis.

- Predictability of degradation and failure levels
  As a result of technological differences, there are inherent differences in the nature of decision problems. Track M&R proved to be a field that allows condition-based strategies and optimisation (clustering), but it remains to be seen whether this is also possible in other technical areas. Some participants also advocated the use of LCC, for example, in the power supply and signalling disciplines, while others were not sure of the effectiveness of LCC in those areas. It is sure that other issues are at stake in those areas, such as ‘the increasing use of electronics and software in signalling, information systems, etc’ [Dowling, 2003].

- Process design and management
  Finally, the interviews provided convincing evidence that the design and management of the LCC-based support is itself very important to the (perceived) success of LCC. The appreciation expressed by all interviewees for the process design and management in the third case can be considered a key element to a more effective approach, as suggested below.

The first four conditions mentioned above are largely outside the control span of the analyst(s) providing LCC-based support, while the last condition is clearly within this control span. Because contexts varied considerably and because this author probably went through ‘a learning process’ with regard to LCC support, strong conclusions are not possible. However, the interviews, the process course and the scores given provide clear indications that the process design and management was most successful in the ProRail case. The following principles were mentioned as successful ways to enhance the quality of LCC support, not only by interviewees from ProRail but also by a number of interviewees from the HSL cases (their references are added):

1. Ensuring stakeholder support in advance. Key stakeholders have to be identified and they should be involved as much as possible at moments when choices have to be made. When LCM+ started, more than a year of preparations had already been ‘spent’, which is more calendar time than the project itself. Stakeholder involvement can vary from a joint definition of study objectives and work approach to joint brainstorming and auditing/reviewing sessions. In advance of the estimations and elaboration of solutions, all stakeholders should comment on a list of starting points (TS-int-2, TS-int-9 and TS-int-10). In project organisations, the analysis should be positioned centrally in the organisational chart: supporters of the project and philosophy need preferably to be found at top management level (SA-int-6).
2. The LCC study as a (mini) project organisation. Facilitating a process that produces relatively independent pieces of advice for the ongoing decision-making process requires a stable environment for developing the models and performing the analyses. A small core group of people should be involved fulltime in the exercise, so that they all go through the same 'process of awareness' (SA-int-3). Recognised subject experts in the organisation, from different management and technical areas, should be allowed to participate in an expert panel, which is completely separated from the ongoing daily work (SA-int-3 and SA-int-5). Since they represent different stakeholders, their involvement helps avoid the 'black-box syndrome' among those parties. If the process works out well then they can also function as ambassadors to propagate the results among the stakeholders.

3. Stepped approach based on plenary brainstorm and validation sessions. The approach followed in the LCM+ study assisted in structuring the process and providing progress reports that cover all data; these are required to judge the quality of the study (agreed starting points, solutions (not) elaborated, input data and assumptions). Starting the project with a computer-supported brainstorm session helped to create an open atmosphere and a broad set of alternatives right from the start ('outsourcing'). Completeness in the set of input data and information sources has to be checked at an early stage (SA-int-5), which requires time (4 months in the LCM+ study). Errors found afterwards (in the case studies) were all related to insufficient reviewing, resulting from time pressure.

4. Developing decision alternatives by separate task groups. The HSL studies showed that new alternatives do not 'arise' automatically; apart from an open atmosphere, incentives should be built into the process to encourage the professionals to depart from their habitual set of approaches. The elaboration of M&R solutions in the ProRail study was assigned to special, small teams in regional pilot projects (SA-int-5); the review of their solutions in plenary meetings with the entire expert panel created helpful peer pressure to produce new solutions. The selected regional pilots also added to a 'sense of urgency' for realistic and acceptable solutions, because they were specific and expensive renewal projects.

5. Computer support in the background. If too much emphasis is placed on computer-based analysis, participants can lose the feeling that they can influence the process. In addition, it generally takes considerable effort to change and validate sophisticated models and it might therefore be wise to develop several simpler models, if the situation allows (e.g. SA-int-2). Involving experts in this dilemma might be a proper choice and also avoid problems such as a false belief in the objectivity of the DSS. Apart from the DSS developed during this study, other calculation tools were also used in the second and third case, in order to test the accuracy or sensitivity of the outcomes. There is no objection to such a 'multi-method' approach, because individual tools usually have specific strengths and weaknesses. In fact, the entire process should focus on filtering out incorrect estimations. A clear example is the use of an anonymous questionnaire during the LCM+ project to signal any hidden feelings that participants had concerning the quality of the input.

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60 Professionals tend to have little eye for innovative opportunities; this phenomenon is known as 'pigeonholing' [Mintzberg, 1983]; professionals often assign, so to speak, new developments to existing categories.
The above list suggests general principles, and not strict 'rules', for process design and management, because such rigid rules would conflict with the dynamic, unpredictable character of (strategic) decision-making on design and maintenance policy. Responding to changing conditions and enhancing (favourable) conditions seems an appropriate task for the core analysis team and its 'sponsors' or 'initiators' within the management team. However, these principles seem difficult to maintain in processes with considerable time pressure and changing objectives, such as in the tendering of HSL South. More coordination in advance and more time for analysis in LCC studies on new, unique decisions may mitigate the problems found; a participative LCC process itself does not bring solace, if there are insufficient incentives and/or willingness among the actors involved to analyse life-cycle costs. Nevertheless, LCC-based support may not have to fulfil all possible functions in order to be valuable. Stakeholders can already value LCC for overcoming deadlocks in decision-making processes or for improving the available knowledge, as with the first two case studies.
8. Conclusions and Recommendations

This chapter reflects on the findings of this study. Section 8.1 summarises the key findings. Section 8.2 formulates a set of recommendations for further research. Finally, Section 8.3 suggests organisational conditions that should be more conducive to current efforts to improve the cost-effectiveness of railway design and maintenance processes.

8.1 Research findings in a nutshell

The observed pace of change in railway policy and the establishment of separated infrastructure managers in Europe were the main reasons for commencing this study. Authors and various stakeholders had expressed their concern about the impact of these changes on the quality of infrastructure design and maintenance in a variety of published articles and policy documents. They particularly questioned whether the newly established infrastructure managers would adopt a 'systems view' to their decision-making processes, in which long-term impacts, in terms of system reliability, costs of ownership etc., would be sufficiently considered. The study was therefore set up to answer the following three questions:

1. What changes are occurring in the rail transport system and its environment, and which bottlenecks do they lead to in design and preservation processes?
2. How can a life-cycle-based approach to railway design and preservation be stimulated in today's railway setting, from a theoretical point of view?
3. Is a decision-support approach able to have courses of action developed and adopted, which are expected to be more cost-effective (over the system life-cycle)?

The first research question was answered by analysing the 'management change' and R&D programmes initiated by a number of reformed railways; findings and conclusions can be found in Section 2.4. It was found that the bodies responsible for the rail infrastructure are increasingly expected to tailor their design and preservation processes to defined service levels, in terms of reliability, availability and safety. This is in sharp contrast to the previous decades, during which they were allowed to carry out their tasks in a fairly operational way, as part of state-owned or state-supported integrated railway companies. European Standard 50126 demonstrates this shifting attitude to rail infrastructure management particularly well.

Several impacts were identified of the changing expectations concerning design and maintenance processes performed by the infrastructure managers (IMs). Firstly, this change is
reflected in a changing internal organisation. In addition to technical skills, contract management and maintenance engineering skills are gradually incorporated. Performance-based management contracts are required, also within the organisation, to replace the usual ‘implicit’ approach to decision-making which is based on individual, subjective judgements by technical staff. An IM such as ProRail even decided to decentralise decision-making powers to ‘maintenance regions’ and to outsource large parts of that process to contractors, which were considered better capable of managing the maintenance process efficiently, also based on their knowledge of the local situation. Several IMs are also investigating the merits of auditing, benchmarking and life-cycle cost analysis; some have recently invested in computerised systems, which should eventually be used to plan maintenance based on measured, empirical data.

Although all R&D initiatives seem focused on creating a process to tailor technical design and maintenance strategies to achieve defined ‘levels of service’ (e.g. reliability and affordability), it was noticed that the R&D is fragmented and that practices on the ‘work floor’ (at the IM) have hardly changed. The actual decision-making process was hardly ever based on quantified expectations of system-wide decision impacts. Life-cycle costing, maintenance planning systems and costing frameworks (which allocate budget on the basis of long-term performance impacts), rarely played a role in decision-making, despite the aforementioned efforts. This conclusion is well illustrated by the call from the US Transport Research Board (A2M01 and A2M06) for R&D into:

- the supply of information regarding the economics of improved design versus maintenance costs;
- planning models and predictive degradation models for non-heavy haul lines; and
- general design principles for computerised planning support, which include key asset data and quantitative business and engineering rules.

The current state of the art causes a threat of sub-optimisation (i.e. ‘too much money paid for too little value’) and a fire-fighting approach, resulting from pressures on the European IMs to improve infrastructure availability, reliability and affordability quickly.

The second research question was answered by studying literature on industrial engineering (maintenance engineering and engineering economics) and public administration; findings and conclusions can be found in Sections 3.6 and 4.5. It was expected that an approach that can ensure the timely supply of rough quantitative insights on long-term costs and performance by utilising ‘tacit’ expert knowledge in the organisation, could be highly useful in assisting decision makers; ingredients for such an approach were expected to be available in the aforementioned fields. The literature study revealed that many industries were already recognising the above challenge to develop design and maintenance strategies that can provide defined levels of reliability and life-cycle costs. The usual ‘maintenance engineering’ approach is to analyse quality degradation patterns of assets and to develop preventive or predictive (condition-based) maintenance tasks based on the criticality of individual assets to the entire system. Finally, these tasks are clustered into work packages based on ‘scale and scope effects’ (e.g. unit costs). The most advanced stage of managing maintenance is referred to as ‘life-cycle management’ (LCM): maintenance and other ‘downstream costs’, including production losses, are analysed from the first planning phase of new systems onwards. A
variety of methods and concepts are available to support the maintenance engineering process, but there is no conclusive theory on how to deploy them consistently, probably due to the variety of systems to be maintained. The literature suggested that it is better to focus first on ‘quick wins’ in order to show the possible benefits of a systems view.

These quick wins can often be found in a few assets which ‘drive’ the system’s life-cycle costs, and several authors recommended Life-Cycle Costing (LCC) as an appropriate vehicle to study the design and maintenance choices around these assets. Although systematic evaluation studies were not found, several authors stated that LCC could already function, to some extent, in environments with a low quality of maintenance data. The reason mentioned is that LCC models are highly suitable for including expert judgements and for testing the robustness of outcomes.

Literature on public-sector management recommended that both analytical and process aspects need to be dealt with in order to gain further progress in multi-actor decision-making process. A technical LCC exercise, outside of the real-life design and preservation processes, would therefore have little chance of success in improving the quality of decision-making. The concept of a decision-support system (DSS) seemed suitable to provide quantitative insights into life-cycle costs, while being responsive to the dynamic, ad-hoc character of multi-actor decision-making. A DSS structure, consisting of a database and model-base for estimating life-cycle costs of rail infrastructure, and a computerised DSS prototype were developed. A pilot study indicated that the DSS prototype developed could generate the desired type of quantitative data on life-cycle costs and performance, although specialist support by a ‘DSS chauffeur’ was inevitable.

In order to answer the third research question, the decision-support approach was applied and revised during three large real-life decision-making processes, each taking place in a different setting (see Table 8.1); the effects of the approach were later evaluated, based on structured interviews with the participants.

<table>
<thead>
<tr>
<th>Table 8.1: Classification of case studies</th>
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<tr>
<td>Direct problem owner</td>
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<td></td>
</tr>
<tr>
<td>Pilot study</td>
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<tr>
<td>Case 1 (HSL South)</td>
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<td>Case 2 (HSL South)</td>
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<td>Case 3 (LCM+)</td>
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</table>

Findings and conclusions can be found in Section 7.5. The three case studies provided considerable information on the usability of LCC in a ‘participative analysis process’, in which stakeholders are actively involved. Participants appreciated the LCC-based support, to a varying degree, for five functions in their decision-making process, i.e.:

1. Identifying decisive cost drivers and performance killers.
2. Validating and invalidating ideas on system-wide decision impacts.
3. Assessing the effectiveness of a broad range of decision alternatives.
4. Changing basic attitudes and mutual understanding, i.e. willingness to reconsider earlier
   standpoints (‘reframing’, as policy analysts would say).
5. Creating commitment to the preferred design or M&R strategies.

However, only the first and second functions were realised satisfactorily in all three
cases, while unambiguous, significant improvements in the decisions taken were only
recognised in the ProRail study. The interviews provided evidence of a number of conditions
that can explain this outcome. These conditions included (top) management support, the
availability of empirical data, and the way the analysis is organised (process design and
management). Involving stakeholders was found to be the most challenging task when
providing LCC-based support, because life-cycle cost analysis crosses traditional boundaries
within the organisation. In some cases, actor commitment and the quality of input data can be
strongly related; actors can also develop a negative attitude if they are not involved in the
analysis.

The participants had recognised a number of process principles, which probably have
contributed to the relative success of the ProRail study, compared to the other two studies,
i.e.: mobilising management support in advance; setting up the study as a more or less
separate project (organisation); installing a permanent panel of experts from different parts of
the organisation; allocating the DSS a background role; and assigning the development of
alternatives to separate, partly competing groups of experts. It was, however, noted that a
participative process also does not seem to bring sustainable results, if a basic willingness
among the actors involved to analyse life-cycle costs is missing.

8.2 Recommendations for further research

This section presents recommendations for further LCC and LCM research in general and for
specific LCC research in the rail sector. The leads towards further research and applications
result from aforementioned findings and the limitations of this study, such as a focus on
(railway) track design and renewal in the case studies and the use of LCC and expert
judgement as primary input sources.

Firstly, this research showed that railway design and maintenance usually takes place
in a multi-stakeholder setting, in which individual commitment is a crucial factor for progress.
In contrast, the LCC and maintenance engineering literature rarely include ways of involving
stakeholders in LCC studies such that the odds of adopting life-cycle-based solutions are
increased. Future research could focus on developing more knowledge on ways of balancing
analytical and process requirements in LCC. Its relationship to other maintenance engineering
methods could also be better studied (see Section 3.4). It is expected that many handbooks
foccussing on the technical aspects of LCC urge practitioners to pursue sophisticated models,
while ignoring the process side; this may render LCC studies ineffective. Without the
participation of important actors, LCC studies may well remain limited to small, theoretical
research projects. Although they may provide important results in the longer term, they do not
help the organisation to embrace a life-cycle approach, because deeper ‘knowledge,
commitment and cooperation problems’ within the organisation are not resolved.
The decision-support approach taken here is expected to be more effective in producing strategies that are accepted in practice and are based on the best available knowledge; however, additional data and observation is necessary to validate this expectation. A prerequisite is that the LCC study initiates a process of continuous improvement for the problem owner, in which new empirical data is sought in order to verify earlier expert judgements. For example, experience shows that expert judgements of maintenance levels are sometimes too negative, particularly in the case of infrequent maintenance [Veit, 2003]; this is possibly because experts tend to remember bad situations better. Plausibility tests are needed to ‘calibrate’ expert judgements, using available empirical evidence. This requires an open attitude by the actors involved, where previous possible misjudgements are recognised frankly (a kind of ‘assumption-based planning’).

Secondly, the DSS prototype used and revised in this study was only intended to support actual needs during the case studies, in the face of limited resources. This means that knowledge of the preferable design of LCC models in a ‘decision-support mode’ is still limited to the decisions supported in this research. Moreover, the implementation in MS Excel did not easily allow the inclusion of optimisation features (e.g. with respect to constraints such as allowable slot times and expenditure profiles) and sometimes led to considerable reworking, which obstructed this author in guiding the first HSL South study. Future research could focus on developing a modular DSS based on joint European starting points for LCC (e.g. including residual values, costs of lost production, and discount rates). A simple DSS structure could be installed, which can be extended over time by adding extra and better models (e.g. degradation models). This DSS could be established as ‘open source’ software, accessible by developers (research institutes) and users (IMs) through the Internet. Ideally, such a DSS enables improved benchmarking of maintenance practices between infrastructure managers, leading to optimised practices at a European level.

Thirdly, this research confirms that LCC is not only useful for designing and procuring new systems (which are the usual topics of LCC handbooks) but, at least in the railway sector, LCC is also useful for reviewing maintenance and end-of-life decisions. As the LCM+ project showed, even at several locations that had been recommended for renewal by M&R planners, beneficial strategies of life extension and reuse could be found. Equally important, LCC contributes to ‘knowledge management’ in preserving railway networks; tacit knowledge is captured, which can be validated and improved using empirical data in order to develop well-grounded M&R practices. However, it would be better to mainly concentrate LCC efforts into dedicated studies that cover an entire technical discipline. The approach currently in use at ProRail, in which M&R planners are (only) obliged to submit an LCC report to the Finance and Control department for every decision over € 0.5 million, risks LCC becoming a bureaucratic protocol or strategic tool for getting project proposals accepted. A variety of experts (both inside and outside the organisation) should participate in order to guarantee a trustworthy process. The following topics are suggested because they have not yet been (fully) explored in this research and others:

1. Track and switch renewal proved to be an area of high impact and high potential for improvement (see Chapter 6). The LCM+ case study was actually a global LCC study. Further study in the Netherlands should focus on analysing feasible (economic) tonnage levels under well-defined operating conditions (e.g. radii, soil conditions, preventive
maintenance, and traffic load), similar to the studies performed in Austria [Veit, 2003]. A refinement of the LCM+ rules could be a useful starting point for further study (see Section 6.7), but also more attention should be paid to preventative strategies. Where possible, this research should be based on actually realised maintenance cost levels and information from other railways, both in Europe and overseas. Attention should also be given to the use of consistent technical criteria for track M&R (see Section 6.7), which may require the development of computerised maintenance management tools (see Section 3.4.7).

2. Switch maintenance also appears to be an area in which significant improvements are possible. Most inspection and maintenance tasks are still calendar-based, at least in the Netherlands, which indicates room for more predictive maintenance strategies [Booij et al., 2004]. Despite the apparently limited usability or accuracy of available data on switch failures and maintenance, LCC could be used to assess the effectiveness of modern monitoring and maintenance regimes for switches in the Netherlands; the REMAIN project provides clues for the study approach (see Section 2.3.3).

3. An analysis of the effectiveness of ProRail’s reliability improvement programme is recommended, because this could help developing a top-down view on budget allocation to the technical subsystems or disciplines. Traditionally, budget is mainly granted to these disciplines on the basis of bottom-up requests. In addition to margins found in track renewal budgets, the need to improve system reliability is another reason for a cross-system analysis. The second case study demonstrated that LCC can function as a vehicle for analysing optimal investment levels across the different technical disciplines, on the basis of expected improvements to infrastructure reliability and durability (see Sections 5.5 and 5.6). Part of this analysis could involve the composition of LCM+–like policy rules for technical systems other than track (e.g. for the overhead line). The focus in the analysis should be put on traffic disruption, and not on the number of unplanned possessions, irrespective of their duration, as is currently the case in ProRail’s performance contract. The reason is that this can lead to wrong priorities in maintenance planning. For example, when ProRail announced (in 2001) a 13% reduction in disruptions, punctuality actually dropped by 1.4%. Long infrastructure-related failures caused this drop; efforts spent on reducing short disruptions had apparently little effect on punctuality [ProRail, 2003c].

4. Analysis of the (potential) impacts of performance, possession and user charging regimes is also suggested as a topic for LCC research. The first case study, which was meant to select between different track systems, showed that LCC study could also indicate possible impacts of the performance and risk allocation regime for the future Infrastructure Provider (see Sections 5.3 and 5.4). LCC may therefore also be used to indicate such impacts on the performance-based user charging and possession regime, to be introduced between ProRail and the operators. This analysis should study the impacts of such a regime on the cost-effectiveness of the entire system; for example, perhaps user charges will result in (disproportionate) negative impacts in terms of the budget available for train maintenance. Such risks could then be quantified and dealt with, in cooperation with the Dutch government.

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Notice that the recent study of Eilander and Taubert [2004] provides an additional starting point with respect to the re-use and reconditioning of rails.
5. **Auditing of construction and upgrading projects** is suggested as a final topic. The UIC InfraCost study revealed considerable differences in cost levels between construction projects performed by the various IMs; it was concluded that ‘overall investment costs could obviously be reduced substantially, if every railway were to attain the “best-in-class” cost position’ [UIC, 2002]. LCC can function as one of the tools in an overall value engineering (VE) approach (see Section 3.4.6). VE aims to eliminate ‘unnecessary functionality’ in construction projects, while LCC should avoid cuts in project budgets that result in higher costs of ownership and operation in the longer term. Both finished and planned projects could be studied for clues to improving the cost-effectiveness of railway upgrading.

Fourthly, it was found that there is now a substantial body of knowledge regarding ‘maintenance engineering’ and a variety of methods for dealing with RAMS and life-cycle cost management; yet, a conclusive theory on how to effectively deploy those in the introduction of a life-cycle approach is not available. Academic research could focus on developing knowledge with regard to ways of using the available set of concepts and methods; for introducing life-cycle approaches more effectively in infrastructure sectors. A research question may be how policies of individual actors should be coordinated with regard to life-cycle effects (e.g. which actor should be responsible for which decisions, data and risks). This theoretical ‘life-cycle management model’ could then be confronted with daily practice. Attention should also be paid to developing ‘paths of migration’ to reach the desired situation. The public administration literature could be utilised to facilitate decision-making processes on required changes, while the rail sector could serve as an example. Figures 2.6, 2.7, 2.17, 3.15 and 4.2 as well as Smit [2000] and Stavenbuiter [2002] can serve as departure points for defining necessary organisational procedures and information and decision-support systems.62

Fifthly, more attention should be paid to the process of dealing with uncertainty when estimating life-cycle performance. Dealing with uncertainties and risk has recently received considerable attention in the literature; an example is the emergence of ‘real options theory’ for valuing the flexibility of decision alternatives (see Section 3.5.2). The analysis of risks and the value of ‘flexibility’ is of particular importance for the rail sector when developing network-wide design, maintenance and upgrading strategies. For example, the LCM+ case study (Chapter 6) could in fact be considered a preliminary study on the possible effects of different possible measures in the planning of track renewal (e.g. clustering, life-extending maintenance and longer track possessions). Because analysis tools were not available, a limited network-wide application was assumed. However, it could be valuable to study the consequences of more drastic policy changes; e.g. it is known that strategies such as the clustering of renewals, combined with life-extension of the ‘weak’ track segments, lead to stronger cyclical quality levels [Plasmeijer, 1999], which will affect the distribution of future M&R over the years. This may result in risks regarding traffic disruption and market prices for M&R work. Moreover, attention should be paid in the impacts of M&R policy regarding future safety and (transport) capacity levels. Finally, it would be compelling to study the ‘willingness to pay’ of taxpayers for different average quality levels of the rail network; such studies are available for new infrastructure [Bengochea and Del Saz, 2004], but may also have value for policy-making on the preservation of existing infrastructure.

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62 Fortunately, progress on this issue is made in the OPC+ project by ProRail and the contractors.
8.3 Suggestions for the rail infrastructure sector

This section suggests changes in data collection systems, organisational procedures and skills, which should contribute to a better breeding ground for analysing and improving the quality and cost-effectiveness of railway design and maintenance decisions. Suggestions arise from the conditions found to stimulate and hamper LCC (see Section 7.5) and are primarily based on ideas from the ‘systems engineering’ and ‘policy science’ disciplines (see Sections 3.4 and 4.1). They are initially directed towards the Dutch rail sector, being the setting of this empirical research, but based on the investigation in Chapter 2 it is expected that many of them make sense at a European level. This is left as a suggestion for further research.

Firstly, all case studies experienced relatively large problems in collecting accurate input data. This was partly unavoidable due to uncertainties in expectations on future operating and maintenance conditions but, to a large extent, those problems were due to inadequate systems for processing information on the maintenance process. In the past empirical records have primarily been kept for the purpose of (a) general accounting of labour hours and cost levels in annual reports and (b) operational, short-term maintenance planning, such as the elimination of faulty geometry. For maintenance management and LCC purposes, the ‘raw data’ needs to be processed and ‘condensed’ into histories of individual assets, including traffic loads carried, defects, condition degradation and performed maintenance. This should allow the development of quality and performance indicators, trend analysis and predictive maintenance strategies, benchmarking of maintenance cost levels, and the composition of up-to-date ‘asset profiles’ containing statistics on lifespans, traffic and maintenance work loads. Data for the linear assets, such as tracks and overhead lines, needs to be condensed into uniform segments or sections, which requires an appropriate database concept and maintenance planning tools. The benefits that it provides for root-cause analysis of cost and performance problems seem evident (see the case studies by Roney on rail reprofiling, in Box 8.1, and by Keefe [2001a] on preventing rail damage at weld-points).

Box 8.1: The Canadian Pacific Railway’s Coal Route [IHHA, 2001, pp. 4/11-4/23]

| It was possible on this highly curved route, from southeast British Columbia to Vancouver, to increase average rail life from 325 million gross tons (mgt) in 1970 to 680 mgt in 2000, while rail and sleeper damage was actually increasing in 1970. This improvement was the result of a set of measures, such as the introduction of an effective regime of frequent rail reprofiling, the adoption of new, so-called ‘worn’ wheel profiles and a ‘computerised analysis of wear rates in order to project the optimal time for rail renewal’. The strategies, which also had positive effects on wheel life (increased by 60%) and other operational costs, did not come out of the blue, but resulted from ongoing research and trial-and-error. For example, the finding in 1970 that ‘the rail grinding was ineffective in preventing the re-occurrence of corrugations’ was one of the reasons to look for a different approach. It was also discovered that, in Australia, success had been achieved with profiling to asymmetrically reshaped rails; this led to an in-depth research study and, in the end, to a new and highly effective grinding regime. |

It is suggested that the North American pragmatic research approach, entirely focussed on reducing the so-called ‘stress state’ of the rail and track system, is followed [see Hawthorne and Kalay, 2001]. Although the North American ‘heavy haul’ operators are clear competitors, they manage to perform much research jointly. The reason for that is evident: first of all, they need to compete with the road system, and cost savings and performance
improvement are of utmost importance for all of them. The current development of InteRRIS (Integrated Railway Remote Information Service) is one of the examples; it will provide users with 'the capability to make predictive, condition-based maintenance decisions' with respect to the interface between train and track [Hawthorne and Kalay, 2001]. The European IMs should also coordinate this type of R&D work better, for example through the newly established European Rail Research Advisory Council [ERRAC, 2003].

Secondly, the case studies and ex-post interviews revealed that there are organisational factors which cause that the aforementioned system for processing information is still not functioning as it should. Although the Production Planning Cycle is in theory focused on collecting and using well-defined asset data (see Section 2.3.1), the regional staff seem in practice to have few incentives for developing the aforementioned type of (accessible) data. The first priority seems to concern securing budget and 'production' (track renewal) levels for the coming year(s), while dealing with daily hassles such as the acquisition of track possessions and the control of outsourced work. As long as this can be secured, there may not be any incentive to systemise knowledge on cost/performance-levels. A serious quality reviewing process concerning the Production Plan, which could evoke such an incentive, seems to be missing, possibly due to the limited resources and decision power of the central ProRail staff responsible for (introducing) maintenance management.

It is recommended that ProRail composes a team at central level, which is responsible for the quality management in the track maintenance planning process, in order to guarantee the development of optimal maintenance strategies from a national perspective. This group should be authorised to organise studies, such as recommended in Section 8.3, as well as regular audits and benchmarks of cost/performance-levels between different lines and regions, in order to incorporate expert knowledge from outside the organisation. The group could consist of both 'content experts' from the various technical fields and people who are trained in maintenance engineering skills [EFNMS, 1999]; although there are such people at central level, they are not explicitly responsible for taking care of this review process. The group should propose central yardsticks for regional work plans and could also become responsible for up-to-date M&R forecasts that form the basis for negotiations with the Ministry of Transport. An additional idea is to grant a substantial part of the regional budgets in advance of such final negotiations, in order to allow regional planners to develop timelier, better maintenance plans; this may well involve them more in the process of improving the IM's overall performance. Supplements can then be provided after final negotiations and audits, perhaps including 'performance incentives'. Finally, the group could become responsible for resolving bottlenecks in the processing of information; in that case, they should be able to commission and involve 'quality circles' of maintenance staff. Participation of the contractors...
is important as ‘tacit knowledge’ obtained by experience in the field is increasingly shifting from ProRail to the contractors. The following concrete suggestions are made:

- Is it possible to implement in the short run a (computerised) track maintenance planning system, using a set of standardised condition thresholds or criteria (‘damage features’) for major track maintenance and renewal, which have been agreed upon at national level? This could be a simple, rough system at first, which is refined over the years.
- How can the current process of recording and analysing infrastructure failures and M&R costs be improved (e.g. which types of defect, maintenance and cost data should be shared in data systems between ProRail and the OPC maintenance contractors)?
- How can a proper database of asset histories be composed and how can the process of updating and usage (statistical analysis, degradation modelling) best be organised?

Thirdly, the finding that European IMs have difficulty in guaranteeing levels of output, such as reliability, availability and affordability (long-term costs of ownership), has also consequences for the national governments, which are the directly or indirectly funding the railway construction and maintenance. It can be stated generally that a Ministry of Transport, being the main financier, is responsible for introducing incentives to encourage a ‘value-for-money’ approach by the IM; as mentioned in Chapter 1, the emphasis at EU level is placed on introducing infrastructure charging principles, but the effect may be limited as often the IM’s revenue generated from user charges is small. The introduction of incentives in the funding regime between IM and national government may therefore be more effective. In the Dutch rail sector, this implies that the development of long-term cost projections (including costs of traffic disruption) should be further stimulated; the IM should be challenged to explain realised lifespans and reliability levels. The Dutch Ministry of Transport may therefore tighten regulation of maintenance cost estimations for new lines and introduce such regulation for technical policies in the maintenance of existing lines. Where possible, track renewal funding should be placed on an equal footing with the other disciplines; today’s funding focuses on ‘budget management’, i.e. ensuring that ‘funds are spent at the time and for the purposes for which they were budgeted’ [Gifford and Stalebrink, 2001]. The Ministry and ProRail could study the use of a depreciation approach or of a fund that allows project-related grants (irrespective of the exact year of periodic maintenance or renewal). Regulation regarding accounting systems for infrastructural assets in North America could serve as an example (see Section 3.1). Finally, the Ministry of Transport could choose to sponsor R&D activities and facilitate decision-making when hurdles for a life-cycle approach need to be overcome. An example is the introduction of equipment that is initially more expensive than the ‘installed base’, but that will result in lower total life-cycle costs.

66 Problems need to be resolved with respect to including and updating the ‘linear asset data’ in the (SAP) databases (the linkage of measured cost, traffic, defect and condition data to specific assets) and in the process of collecting key statistics regarding life spans; infrastructure data are often lost, once new data are entered after renewal. The developments around GIS-based systems and IRISsys seem most promising for improving the data processing in ProRail. All in all, the ‘management of scope’, i.e. the feedback process regarding changes in and real impacts from the maintenance and renewal activities seems to need significant improvements.

67 The cash funding (fond perdu) will encourage ProRail staff to focus on a ‘comfortable’ budget acquisition, in combination with an insufficient ‘quality review’ of the Production Plans (see Chapters 6 and 7). As mentioned in Section 6.1, other technical disciplines in ProRail possibly face serious budget shortages because of insufficient depreciation plans [see the multi-year plan of ProRail].
All in all, governments need to be cautious in introducing, all at once, severe 'performance contracts' for IMs, considering the actual state of maintenance management in the European railways. Performance regimes ideally create positive incentives to analyze and control all kinds of cost drivers better, such as the impact of the quality of rolling stock entering their system or the quality of welds on infrastructure degradation. However, at the moment, the IM often receives conflicting incentives from the funding side (e.g. in the case of cash-based funding, the IM is not awarded for a better cost performance). Moreover, it is yet difficult to develop an encompassing 'performance management' system, and the term 'performance' is therefore often narrowed down to 'reliability' only. This encourages the IM not to give equal priority to items such as improving infrastructure life expectancies (durability) and, last but not least, safety (measurable through, for instance, signals passed at danger). Further, it encourages the IM to claim increased budgets without solving root causes. The developed decision-support approach alone – and perhaps any approach – may not be able to significantly mitigate such tendencies in decision-making, as long as an appropriate funding and auditing approach does not support this. Posing challenging questions to the IM, relating to realised lifespans, reliability and maintenance cost levels, could therefore perhaps be more effective for the progress in (railway) maintenance management than developing advanced performance contracts.
In addition to the technical issues that characterize the wheel/rail system, there are very important economic issues. It is essential to take into account a cost/benefit analysis in the course of making technical decisions. These are illustrated in the following remarks.

Rail is the single most expensive element of the track structure. On many railways, it is behind only labor and fuel as an expense item. The tonnage carried by a rail before it is condemned can range from less than 100 million gross ton to close to 2.5 giga gross ton.

As an example of the value of rail maintenance management, assume that a single kilometer of rail costs $180,000 to install. Track engineers decide that the rail has a badly fatigued surface and has reached the end of its service life. They call for it to be replaced, gaining a salvage value of $18,000.

But now assume that instead of replacing the rail, they did some corrective rail grinding costing $1800 and left the rail in track. The railway then invested the $180,000 - $18,000 = $160,200 in the construction of a new customer facility at a rate of return of 20%. This earned $160,000*20% = $32,000 in its first year.

The next year, the track engineers see that their rail is approaching allowable wear limits and schedule a rail replacement, now costing $187,200 due to cost escalation of 4%. But they have made for the railway $32,000 - ($187,200-180,000) = $24,800 by deferring replacement of rail in that kilometer, without consequence, for an extra year. And that is why they collect a salary.

There is significant money to be made by deferring rail replacement as much as possible without incurring risk. Certainly it is a major responsibility of the track engineer to ensure that he gets the most out of his rail, and rail profile maintenance and rail testing are his most important tools to do this.

_Taken from 'Best Practice in Heavy Haul', p. 1-10, International Heavy Haul Association (IHHA), Virginia Beach, U.S.A., 2001_
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Zeta-tech (1998) Model for determining and negotiating shared costs or open access charges on railway lines, Zeta-tech, New Jersey.


Zoeteman A. (2000c) Results of the optimisation sessions for the HSL South rail system, DUT and FastRail Consortium, Maarssen.
Appendices
A: Interviews 1997-2001

This appendix lists the persons that were interviewed during this research project. Reports were made for each of these interviews. First of all, interviews were held in order to support the exploration on the state of the art in maintenance management (see Chapter 2). Interviewees included experts and decision makers, both in the Netherlands and abroad, whenever there was an opportunity to visit leading railways or research institutes. Interviews were used to explore new developments in the management of railway maintenance as well as LCC applications.

Most interviewees expected that LCC could be used to provide a link between the technical staff and the management, but that experience with LCC so far was limited or absent. One interviewee mentioned an LCC study for the new Betuwe Freight Line, which had a projected cost of € 4 billion at the time. Decision makers considered using UIC54 rails instead of heavier UIC60 rails, due to huge budgetary problems; this would save € 4 million. The LCC study clearly showed the negative impacts on costs and track possessions during the operational phase of the railway, which could not justify this small saving. As the particular interviewee notes, LCC can thus provide a ‘common language’ between technical staff and managers, and can distinguish between matters of major and minor importance. Others mentioned that LCC could help provide a specified performance level cost-effectively. As one interviewee mentions, LCC can be used to settle priorities based on the opportunity costs of investments: ‘If we can save one million euro with a relatively small investment here, but this same investment can save 10 million euro there, then we have to do the investment there and not here’. Further, the Preservation Division can use LCC to develop maintenance specifications for new designs made by the Construction Division. Finally, an interviewee mentioned that LCC can be used as an instrument to manage contracts between maintenance contractors, the IM and the Ministry of Transport. It could be a tool to motivate required performance fees and to analyse the impacts of particular events.

Interviews were also held to evaluate the case studies. This last category of interviews was used for Chapter 7; the sequence of persons listed does not match the interviewee reference numbers in the running text of Chapter 7. Only the particular interviewee and the author know this number, which was included in confidential interview reports. Appendix B provides the list of questions.

National exploration on maintenance management, quality control systems and LCC
Mr Hans Bouwman, ProRail/RIB B&I (September 29, 1997)
Mr Ton Beckers, ProRail/RIB B&I (September 29, 1999)
Mr Theo ten Brake, ProRail/RIB B&I (September 22, 1997)
Ms Linda van der Eijck, ProRail/RIB B&I (GRIP meetings in 1998 and 1999)
Mr Gerrien van der Houwen, Edilon (September 26, 1997)
Mr Frans Klösters, ProRail/RIB B&I (September 29, 1997)
Mr Frans Kluijn, Holland Railconsult (September 15, 1997)
Mr Dik de Koning, ProRail/RIB B&I (May 11, 1999)
Mr Ollie Olsthoorn, ProRail/RIB B&I (GRIP meetings in 1998 and 1999)
Mr Gerrit Rees, HTM (October 3, 1997)
Mr Johan de Ruiter, ProRail/RIB B&I (October 13, 1997 and May 4, 1999)
Mr Diederik Schonebaum, Strukton Railinfra (GRIP meetings in 1998 and 1999)
Mr Aike Schoots, Strukton Railinfra (GRIP meetings in 1998 and 1999)
Mr Pim Schram, Edilon (September 26, 1997)
Mr Sjoerd Sjoerdsma, ProRail/RIB B&I (May 11, 1999)
Mr Gerard Snippert, ProRail/RIB AKI (July 27, 1997)
Mr Jan Swier, ProRail/RIB B&I (May 28, 1999)
Mr Bart Swiers, ProRail/RIB AKI (July 27, 1997)
Mr Erland Tegelberg, Strukton Railinfra (GRIP meetings in 1998 and 1999)
Mr Ton Weel, NS Ultrasoonbedrijf/Eurailscout (September 19, 1997)
Mr Jelle Zijlstra, Strukton Railinfra (September 15, 1997)

**International exploration on maintenance management and LCC (sorted by date)**
Mr R. van Leeuwen, NMBS/SNCB (Brussels, April 1, 1999)
Mr A. Comrie, Spoonet (Utrecht, May 4, 1999)
Prof. W. Ebersöhn, University Of Pretoria, Amtrak (Utrecht, May 4, 1999)
Mr S. Handa, JR West (Osaka, October 14, 1999)
Mr A. Tanimoto, JR West (Osaka, October 14, 1999)
Mr Furukawa, RTRI (Tokyo, October 25, 1999)
Ms Kamiyama, RTRI (Tokyo, October 25, 1999)
Mr H. Takai, RTRI (Tokyo, October 25, 1999)
Mr K. Ando (Tokyo, October 26, 1999)
Mr Asunuma, RTRI (Tokyo, October 26, 1999)
Mr T. Ishikiwa, JR East (Tokyo, October 26, 1999)
Mr M. Miwa, Graduate Institute for Policy Studies (Tokyo, October 26, 1999)
Mr K. Arie, JR Central (Tokyo, October 28, 1999)
Mr N. Ikeda, JR Central (Tokyo, October 28, 1999)
Mr V. Rano, JR Central (Tokyo, October 28, 1999)
Mr Y. Naganuma, JR Central (Tokyo, October 29, 1999)
Mr E. Aoki, JR Central (Tokyo, October 30, 1999)
Mr Y. Goto, JR Central (Tokyo, November 1, 1999)
Prof. Y. Sato, Nippon Kikai Hosen (Tokyo, November 2, 1999)
Mr A. Chan, Mass Transit Railway (Hong-Kong, June 5, 2001)
Mr T. Wong, Mass Transit Railway (Hong-Kong, June 5, 2001)
Mr M. O'Brien, Kowloon Canton Railway (Hong-Kong, June 6, 2001)
Mr P. Chan Po Loi, Kowloon Canton Railway (Hong-Kong, June 6, 2001)
Mr J. Brennan, Queensland Rail (Brisbane, June 15, 2001)
Prof. L. Ferreira, Queensland University of Technology (Brisbane, June 15, 2001)
Mr B. Greening, Rail Infrastructure Corporation (Sydney, June 19, 2001)
Mr S. Silva, Rail Infrastructure Corporation (Sydney, June 19, 2001)
Mr A. Petlevanny, Rail Infrastructure Corporation (Sydney, June 19, 2001)

**Evaluation of HSL Track Selection case (during the spring of 2000)**
Mr Egbert Braaksma
Mr Hugo Goossens
Mr Steffen Knape
Mr Dirk van Meeteren
Mr Marco Reef
Mr Frits Schippers
Mr Diederik Schonebaum
Mr Aike Schoots
Mr Frans Spronk
Mr Erland Tegelberg
Mr Johan Vergeer
Mr Hans Wenkenbach
Mr Jelle Zijlstra

_Evaluation of HSL System Availability case (during the spring of 2000)_
Mr Leen Berke
Mr Egbert Braaksma
Mr Hugo Goossens
Mr André Huber
Mr Richard Klompjan
Mr Hans Nederend
Mr Frits Schippers
Mr Diederik Schonebaum
Mr Harry van Splunder
Mr Johan Vergeer
Mr Peter Vermaat
Mr Hans Wenkenbach

_Evaluation of ProRail Track Renewal case (during the summer of 2001)_
Mr Anno Bloemsma
Mr Dirk van de Greft
Mr Mark Jaspers
Mr Evert Kleinjouw
Mr Kees Loef
Mr Ollie Olsthoorn
Mr Ronald Slieker
Mr Ted Slump
Mr Bert Stormink
Mr Jan Swier
Mr Fred Veldeman
Mr Piet Versteden
Ms Mariken Veth
Mr Frits Vinken
Mr Rob van Zelm
B: Interview questions for the evaluation of the case studies

Interviews were set up to take a maximum of 2 hours. Questions were posed after a brief retrospection of the project. After some introductory (open) questions, the interviewee was asked to fill in a score table. It was stressed at the start and, where necessary, during the interview that his/her answers would be used for the purpose of LCC research and that this author therefore only had an interest in his/her objective judgement on the effectiveness of the decision support provided and ways in which this could be improved.

Specific questions for HSL Track Selection case
1. What is or has been your position in the consortium? E.g. designer track, financial adviser, analyst M&R, manager working group. How long have you been involved in the project?
2. What are the most important aspects of the Infrastructure Provider contract? How has this affected the design and maintenance?
3. What do you think of the requirement of supplying performance (availability, reliability, life-cycle costs)?
4. Will the separation of the substructure and superstructure design have (had) an impact on design choices and costs?
5. Were the most important track alternatives considered sufficiently during the Consultation Phase? What were the reasons for extending or limiting the alternatives during the Consultation and Tender Phases?
6. What was decisive in the final choice (Direct Fastening, Embedded Rail) during the Consultation Phase? Why was this choice seriously reconsidered during the Tender Phase? Did the State’s preferences play a role in this process?
7. Do you think that the track structure(s) with the optimal life-cycle costs have been selected? If not: What would have been the best track structure (according to you)?
8. Was the overall way of working on the joint risk and life-cycle cost analysis transparent? Did it give more insight into the most important cost and risk issues?
9. Did the presentation of the cost breakdown for design and maintenance (by the life-cycle cost model) help you in analysing the various track alternatives?
10. Did it trigger you into reconsidering your design, maintenance and incident prognosis?

Specific questions for HSL System Availability case
1. What is or has been your position in the consortium? E.g. designer track, financial adviser, analyst M&R, manager working group. How much time did you spend on the project?
2. What are the most important aspects of the Infrastructure Provider contract? How has this affected the design and maintenance?
3. What do you think of the requirement of supplying performance (availability, reliability, life-cycle costs)?
4. Were you aware of the impact of the Performance Payment Algorithm from the start of the Tender Phase?
5. Was the crucial information needed for estimating the rail system's performance readily available within the consortium?
6. Do you think that the design with the optimal life-cycle costs has been realised? Why (not)? Which technical discipline has been most important in these costs and would you have expected this beforehand?
7. Do you have confidence in the quality of the final Incidents Matrices and the estimation of delay penalties?
8. Do you think that acquisition of reliable data presented a problem? Was it e.g. possible to benchmark the performance of other European high-speed lines?
9. Were the Optimisation Workshops important? Did they trigger you into reconsidering your design and maintenance? Why (not)?
10. Were you satisfied with the presentation of penalty costs per Incident Category by the model used during the Optimisation Workshops? Did the DSS provide more insight into the most important cost and (penalty) risk issues?

Specific questions for ProRail Track Renewal case
1. What was your role/function in the LCM+ project and did this align with your daily work duties? How much time did you spend on the project?
2. What are the most decisive factors in the planning of track renewals? How do they influence the solutions chosen? What, in your view, is the value and role of the 20-year Track Renewal Forecast?
3. Do you think that life-cycle management will lead to lower life-cycle costs and an improved performance (availability/reliability)? Does LCM provide other advantages?
4. Have the most important solutions for reducing life-cycle costs been included in the LCM+ project, or have solutions consciously/unconsciously been left out of the analysis? Can you list specific examples in relation to the LCM+ pilots?
5. Have the outcomes of the LCM+ project influenced the choices for the 2002 production plan?
6. Was the approach to the LCM+ project clear (from the start)? Has this approach contributed to the realised results? Do you think that this is a sound approach for policy revisions? Could you reflect on specific activities in the approach (GDR, Pilots, Policy Workshop, Final Report,...)?
7. Did the presentation of life-cycle costs and traffic disruption (using the LifeCycleCostPlan) during the sessions from October to February contribute to a better analysis? Did this help you in estimating life-cycle impacts?
8. Do you have confidence in the outcomes? Do you consider the outcomes from the various pilots and the policy rules to be robust? Do you foresee developments in the short term that require changes to the policy rules?
9. What is your view on the cooperation with the other regions? Was it different/better/worse than in other decision-making processes?
10. What do you expect from the implementation of LCM+? What, in your view, should be done with respect to the production planning cycle? Are you prepared to give your support?

General questions concerning the effectiveness of the decision support provided
1. Did the decision support lead to an increased insight into the problem situation and alternatives investigated (or not)?
2. Were knowledge gaps identified as a consequence of integrating data/knowledge?
3. Did the decision support provided favourably affect the decision makers’ agenda (or not)? (Were new items added? Were others removed?)
4. Did the decision support provided contribute to a favourable change in the number of (design or maintenance) alternatives considered (or not)?
5. Did the decision support increase the manageability of the analysis and choice process (or not)?
6. Did the decision support provided contribute to increased commitment to the analysis and outcomes among the stakeholders (or not)?
7. Did the decision support and its findings favourably change the attitudes/positions of the various parties towards the problem (or not)?
8. Did the decision support provided contribute to improved relationships and understanding between the parties (or not)?
9. Did the decision support provided help to reduce the time needed to complete the decision-making process (or not)?
10. Did the decision support provided contribute to an increased 'sense of urgency' of the problem situation and did the awareness of the various parties' responsibilities increase as an effect (or not)?
11. Did the decision support provided contribute to the selection of a cheaper or more efficient alternative (or not)?
12. Did the decision support provided increase the quality in terms of robustness and broadness of the analysis and choice (or not)?
13. Was sufficient time available, considering the complexity of the problem?
14. Did all parties involved in carrying out the analysis receive the required information in time?
15. Was existing empirical data, from various sources, available for the decision support (with sufficient level of detail)?
16. Was there sufficient participation by qualified (technical) staff?
17. Did all parties involved participate equally in the process?
18. Was the time right for the study?
19. Did you have the feeling that you could influence the development and use of the DSS?
20. Was the decision support provided sufficiently intertwined with the decision-making process?
21. Did strategic/unspoken reasons play a role in initiating the study?
22. Were there any other factors influencing the study?
23. What functions did the decision support have in the decision-making process?
24. How was the DSS able to contribute to these functions and to the decision-makers' needs?
25. What are the strengths and weaknesses of using a DSS and how can its effectiveness be improved?
C: Data checklist for LifeCycleCostPlan

The data checklist contains standard tables that are completed by people generating input for LCCP and can be split into a number of elements.

A. Project description (for infrastructure components). System, scope, and time boundaries are described. A qualitative overview of the operations and maintenance history of the components is requested.

<table>
<thead>
<tr>
<th>Item</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOCATION ASSET(S)</td>
<td>Geographical code and ‘mileposts’</td>
</tr>
<tr>
<td>ASSET TYPE(S)</td>
<td>Number and types of switches, track structures, level crossings etc.</td>
</tr>
<tr>
<td>LENGTH ASSET(S)</td>
<td>Number of km or m per asset</td>
</tr>
<tr>
<td>CURRENT AGE</td>
<td>Cumulative tonnage (MGT) and years</td>
</tr>
<tr>
<td>MAINTENANCE HISTORY AND CURRENT STATE</td>
<td>Description of important maintenance activities that have taken place; current quality and reliability of structure/system</td>
</tr>
<tr>
<td>PROBLEM DESCRIPTION</td>
<td>Exact causes for focusing on these assets; any doubts concerning maintainability and safety?</td>
</tr>
<tr>
<td>FUTURE PLANS</td>
<td>Analysis of projects that may influence the assets, e.g. planned corridor upgrades or new functionality demands</td>
</tr>
<tr>
<td>SYSTEM BOUNDARIES</td>
<td>Demarcation of the analysis; which life-cycle aspects will be investigated, which constraints need to be considered (e.g. budget constraints)?</td>
</tr>
<tr>
<td>START YEAR</td>
<td>First year of analysis for (specified) maintenance tasks</td>
</tr>
<tr>
<td>TIME HORIZON</td>
<td>Period considered in estimating life-cycle costs</td>
</tr>
<tr>
<td>ALTERNATIVES</td>
<td>Listing of selected variants with qualitative description, including risks and expected advantages/opportunities</td>
</tr>
</tbody>
</table>

B. Transport performance (for infrastructure components). Data related to tonnage, speeds, axle-loads and transport values are requested for the various railway sections under consideration. Types and quantities of passengers and freight carried may also be relevant.

<table>
<thead>
<tr>
<th>Item</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRANSPORT VALUE</td>
<td>Priority of the corridor for passenger and freight traffic, as expressed in performance regime</td>
</tr>
<tr>
<td>DAILY LOAD</td>
<td>Daily or annual tonnage (MGT), axle-loads etc.</td>
</tr>
<tr>
<td>TIMETABLE AND TRAFFIC CHARACTERISTICS</td>
<td>Reference timetable, including operational and after-hours (i.e. natural gaps in timetable), and characteristics of trains</td>
</tr>
<tr>
<td>SPEED AT LOCATION</td>
<td>Speed of traffic passing the assets</td>
</tr>
</tbody>
</table>

C. Work conditions (for alternatives). Cost and productivity rates, required speed restrictions etc.

<table>
<thead>
<tr>
<th>Item</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATERIAL COSTS</td>
<td>Unit rates for materials (per m or km) for installation or M&amp;R</td>
</tr>
<tr>
<td>COSTS PER SHIFT</td>
<td>Unit rates for manpower and machines (per hour) for maintenance, overhaul and renewal (day/night/weekend rates)</td>
</tr>
<tr>
<td>PRODUCTIVITY WORK METHODS M&amp;R</td>
<td>Distinction between set-up and finishing work and net productivity (m or km per hour)</td>
</tr>
<tr>
<td>POSSESSION REGIME</td>
<td>Which regime is applicable? E.g. 6-hour, 9-hour or 24-hour regime (during weekday/weeknight/weekend).</td>
</tr>
</tbody>
</table>
D. Maintenance needs (for alternatives). M&R thresholds, required spot maintenance etc.

<table>
<thead>
<tr>
<th>Item</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>THRESHOLDS FOR PERIODIC M&amp;R</strong></td>
<td>'Life-cycle activity profile' including expected lifespan (renewal) and years of periodic M&amp;R (grinding, tamping etc.)</td>
</tr>
<tr>
<td><strong>COSTS OF MINOR MAINTENANCE</strong></td>
<td>Expected minor maintenance costs per year or per MGT per km, including costs of failure repair (e.g. using norm costs OPC contracts or Failure Mode Effect Analysis)</td>
</tr>
<tr>
<td><strong>HOURS OF BLOCKAGE DUE TO FAILURES</strong></td>
<td>Expected hours of blockage per year or per MGT per km</td>
</tr>
<tr>
<td><strong>HOURS OF SPEED RESTRICTION DUE TO FAILURES</strong></td>
<td>Expected hours of speed restriction (due to failures and minor maintenance) per year or per MGT per km</td>
</tr>
</tbody>
</table>

E. Functionality impacts (for alternatives). Possible impacts related to aspects such as safety, noise pollution and residual values.

<table>
<thead>
<tr>
<th>Item</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAFETY</td>
<td>Are any safety impacts expected (reduction/increase in risks)?</td>
</tr>
<tr>
<td>NOISE</td>
<td>Are any effects on noise and vibration levels expected?</td>
</tr>
<tr>
<td>SPEED</td>
<td>Will it alleviate/require permanent speed restrictions?</td>
</tr>
<tr>
<td>OTHER IMPACTS</td>
<td>Are there any other effects, e.g. regarding transport capacity on the corridor or riding comfort?</td>
</tr>
<tr>
<td>RESIDUAL VALUE</td>
<td>What is the residual value after the period of analysis and is it expected to differ significantly from other alternatives?</td>
</tr>
</tbody>
</table>

F. Financial parameters (for the entire project). Interest rate, base year, performance payment regime etc.

<table>
<thead>
<tr>
<th>Item</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE YEAR</td>
<td>Year in which decision is made or implemented</td>
</tr>
<tr>
<td>DISCOUNT RATE</td>
<td>This is usually the real interest rate, or discount rate set by national administration</td>
</tr>
<tr>
<td>COSTS OF NON-AVAILABILITY</td>
<td>Penalty rates according to performance regime</td>
</tr>
</tbody>
</table>

Data (from all pilots) from the ProRail Track Renewal case study was included in a single document, using the above tables. Data from the other two case studies was also included in the reports, but not in the above (standardised) manner.
D: First test of the usability of LCCP at Madrid Metro

The first version of LifeCycleCostPlan allowed a pilot study to test the usability of the DSS in February 1998. A research programme by the Railway Engineering Group at Delft University for the Comunidad de Madrid – the Regional Government for Madrid, Spain – provided this opportunity. The research started in 1997 and aimed to review the entire process of maintaining the tracks and switches at the Madrid Metro. The following tasks were defined in the contract:

1. Collect, investigate and compare the current standards for track construction and maintenance of comparable track systems in Madrid and other cities worldwide.
2. Compare the currently applied track structures at Madrid Metro and a few other track systems in terms of performance, constructability, maintainability and costs.
3. Define data-flows needed for a management system that improves maintainability of the track system and increases safety, availability and efficiency.

The Comunidad considered this review necessary because it had started to construct new extensions to the subway network, amounting to more than 35 km of double track, with track laying due to commence in 1998 and 1999. The extension plan and a recent constructional problem were reasons why the Comunidad consulted Delft University. Among other things, a second opinion was requested on the track design, i.e. Edilon block track. The Comunidad opted for a system that would be economical on the long run, which is why the research would include an attempt to 'look at the total life-cycle costs, including maintenance and renewal'. This part of the research, known as ‘Project 2C’, started in February and is described below in the subsections below.

D.1 Research objective and context

The aim was to assess three track systems, i.e. ballasted track, block track, and embedded rails, on their expected life-cycle costs for the Madrid Metro situation. The assessment could well focus on costs of construction and maintenance only, since the choice would hardly influence system availability and reliability; most of the maintenance work was performed during the nightly non-operative time when it did not disrupt traffic. The few track-related failures are hardly influenced by the type of track. The approach taken in the assessments is discussed in Section D.2; first, however, more details are provided on the design and management of the network.

The first 3.5 kilometres of the network, between Puerta del Sol and Cuatro Caminos, were first used in 1919. These two places had become important nodes in a railway network that, in 1998, comprised around 120 kilometres of double-track, standard-gauge line, designed for a maximum speed of 70 km/h, and 164 stations. The line transported 1.5 million passengers daily with headways between trains of 2-3 minutes during peak hours and, outside these hours, 3-5 minutes. Trains run from 6 a.m. to 1.30 a.m., and the network is well linked with the regional railway network, Cercanias, the national RENFE rail network and the AVE

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68 In 2004, the network consists already of 227 km of line and 238 stations, serving 2.5 million passengers daily; a new extension plan for the period 2003-2007 has been authorised.
high-speed line to Seville; ticketing of Metro and Cercanias is integrated. The construction of the new lines was part of an Action Programme that started in 1994 in order to cope with the rapid growth of the population and road congestion.

A number of governmental bodies were commissioned to manage and extend the network; Figure D.1 depicts this network of organisations. A split is made between responsibility for constructing the network extensions and for the daily operation and maintenance. The Directorate-General of Infrastructure, part of the Ministry of Urban Works and Transport, was directly responsible for the new lines, and used parties such as engineering consultants, contractors, auditing companies, and track manufacturers to realise the extension programme. The Madrid Metro Company was responsible for operating the network; it belonged to the Consorcio Regional de Transportes, with the Comunidad and the Municipality (Ayuntamiento) as its shareholders. The autonomous Consorcio Regional had a budget to plan new public transport services, and could select appropriate transport mode (bus, metro or railway service). There were various relations between the aforementioned actors, e.g. the Director-General of Infrastructure was also the Deputy Director of the Metro at that time.

Within this context, the Action Programme 1994-1999, concerning the construction of 37.17 kilometres of new double-track line, was being performed (see Table D.1); the extensions of Line 10 were already finished in 1998. Both bored tunnels, with diameters of 9-10 metres, and conventional tunnels with a rectangular shape were used; a small advantage of the latter was that less supporting concrete was required to flatten the floor for the track system.

<table>
<thead>
<tr>
<th>Line</th>
<th>From</th>
<th>To</th>
<th>Stations</th>
<th>Distance</th>
<th>Tunnel type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Miguel Hernandez</td>
<td>Congosto</td>
<td>3</td>
<td>2.67</td>
<td>Conventional</td>
</tr>
<tr>
<td>4</td>
<td>Esperanza</td>
<td>Parque de Sta. Maria</td>
<td>4</td>
<td>4.45</td>
<td>Bored</td>
</tr>
<tr>
<td>7</td>
<td>Avenida de América</td>
<td>Pitíis</td>
<td>14</td>
<td>10.70</td>
<td>Bored 89%</td>
</tr>
<tr>
<td>8</td>
<td>Mar de Cristal</td>
<td>Barajas (Pueblo)</td>
<td>4</td>
<td>8.23</td>
<td>Conventional 11%</td>
</tr>
<tr>
<td>9</td>
<td>Pavones</td>
<td>Puerta de Aganda</td>
<td>4</td>
<td>4.60</td>
<td>Bored</td>
</tr>
<tr>
<td>10 a</td>
<td>Nuevos Ministerios</td>
<td>Alonso Martinez</td>
<td>1</td>
<td>1.62</td>
<td>Conventional</td>
</tr>
<tr>
<td>10 b</td>
<td>Plaza de España</td>
<td>Junction near Lago</td>
<td>0</td>
<td>2.60</td>
<td>Bored 65%</td>
</tr>
<tr>
<td>11</td>
<td>Plaza Elíptica</td>
<td>Pan Bendito</td>
<td>3</td>
<td>2.30</td>
<td>Conventional</td>
</tr>
</tbody>
</table>

D.2 Research approach and process

It was decided to organise and perform the life-cycle cost analysis at the headquarters of the Comunidad in order to be closer to the construction and maintenance process and to be in direct contact with the key decision makers (the coordinator of the Action Programme and the Director-General). During February and March, data was collected and estimations made with assistance from a couple of knowledgeable staff from the Madrid Metro, contractors and engineering consultants.

An investigation into the functioning of track systems installed on the Madrid Metro network was held first. The main alternatives, ballasted and block track, had both been used for a relatively long time in Madrid; Table D.2 shows the number of track kilometres for both track types in 1996. The first block tracks were installed in the early 1970s and consisted of rigid systems, but systems were soon used that provided more controlled elasticity; mainly the Stedeff and Edilon systems. Prefab Embedded Rails slabs had so far been installed over a small distance at the Príncipe Pío station.

Table D.2: Track structures used on the Madrid Metro network (in metres as of 1996)

<table>
<thead>
<tr>
<th>Ballasted track</th>
<th>Block system track</th>
</tr>
</thead>
<tbody>
<tr>
<td>UIC45 rails</td>
<td>UIC54 rails</td>
</tr>
<tr>
<td>12,181</td>
<td>143,852</td>
</tr>
<tr>
<td>UIC45 rails</td>
<td>UIC54 rails</td>
</tr>
<tr>
<td>15,400</td>
<td>70,506</td>
</tr>
</tbody>
</table>

Total ballasted track: 156,033  Total block track: 85,907

Total network length: 241,940 (passenger lines only, no garages)
After this first investigation, it was decided to concentrate the assessment on ballasted track and Edilon block track. Since all construction and M&R activities had to be performed in a tunnel environment, available facts on ERS were considered unusable. It was decided to provide the Comunidad with a separate report on an ERS application from the Netherlands (for track in the open air). A tunnel environment would require a different process in terms of material logistics and construction methods. Nevertheless the ERS report indicated that ERS could be an attractive option if integration of the track system into the tunnel floor filling is possible.

Three steps were planned for assessing life-cycle costs. Firstly, key characteristics would be identified for the ballasted track, the Edilon system and the Embedded Rails System (ERS), to be considered in the Madrid Metro situation. Secondly, maintenance and renewal data would be gathered for the past few years plus the current costs of construction. Finally, a life-cycle cost comparison would be made for installing the new lines, using data from the new Airport Line to Barajas Pueblo (Line 8) as an example; conditions on any of the new extensions would not differ substantially.

D.3 Research results and recommendations

Description of the decision alternatives
Ballasted track is the track system traditionally used throughout the railway world and is known for its flexibility; it is easy to construct and maintainable, but also needs regular maintenance. On the other hand, block track systems require less maintenance thanks to a fixed geometry, but they require more initial investment. Table D.3 on the next page lists the main pros and cons of these systems including the Embedded Rails System.

The first applications of the Edilon system proved to be more than 40% more expensive than ballasted track; however, in 1998, the entire construction was still only 12% more costly. The blocks were produced in two sites, one of which was the open-air factory in Alcalá de Henares, shown in Figure D.2. The Edilon block system used in Madrid has the advantage that the use of a mixture of cork and polyurethane (Corkelast) provides a controlled elasticity that, in Madrid, is already included during the manufacturing of the blocks. Components needing maintenance, such as ballast beds, are absent; the blocks themselves can be transported and replaced manually in the tunnels. However, avoiding a faulty initial quality requires extra process control when using Edilon block track, not only at the construction site, but also in the design and manufacturing of the blocks. The system is therefore constructed top-down, which enables strict control of the track geometry during construction. Firstly, the rails and the blocks are fixed using fasteners. Then the track frame (consisting of rails, fasteners and blocks) is positioned (see Figure D.2). After finishing this process, the concrete is poured into the tunnel until the level of the blocks is reached and smoothed out.
### Table D.3: Considered track structure alternatives

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Easy construction</td>
<td>- Considerable (ballast) material is needed</td>
</tr>
<tr>
<td>- High elasticity of the ballast bed</td>
<td>- Ballast implies extra weight and height</td>
</tr>
<tr>
<td>- Flexibility of construction (both components and geometry)</td>
<td>- Discontinuous support of the rails</td>
</tr>
<tr>
<td></td>
<td>- High maintenance frequency</td>
</tr>
<tr>
<td><strong>Extra pros and cons for Madrid Metro environment</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Sleepers and ballast are heavy, which complicates manual maintenance</td>
</tr>
<tr>
<td></td>
<td>- Maintenance machinery is costly</td>
</tr>
<tr>
<td></td>
<td>- Transport of ballast is costly</td>
</tr>
<tr>
<td><strong>Edilon block track</strong></td>
<td></td>
</tr>
<tr>
<td>- Fixed geometry</td>
<td>- Little readjustability: accuracy of construction has to be high</td>
</tr>
<tr>
<td>- Ballast is not required</td>
<td>- Blocks are expensive</td>
</tr>
<tr>
<td>- Improved maintainability</td>
<td>- Discontinuous support of the rails</td>
</tr>
<tr>
<td>- Little maintenance</td>
<td></td>
</tr>
<tr>
<td><strong>Extra pros and cons for Madrid Metro environment</strong></td>
<td></td>
</tr>
<tr>
<td>- Blocks can be transported manually</td>
<td>- Transport of concrete compound can cause logistics problems in some locations</td>
</tr>
<tr>
<td>- Tunnel provides excellent support</td>
<td></td>
</tr>
<tr>
<td>- Construction conditions can be controlled</td>
<td></td>
</tr>
<tr>
<td>much better than in the open air</td>
<td></td>
</tr>
<tr>
<td><strong>Embedded rail structure</strong></td>
<td></td>
</tr>
<tr>
<td>- Fixed geometry</td>
<td>- Little readjustability</td>
</tr>
<tr>
<td>- Construction needs less height (20 cm, ballasted track as reference) and is lighter</td>
<td>- Construction is expensive</td>
</tr>
<tr>
<td>- Ballast, blocks or sleepers are not required</td>
<td></td>
</tr>
<tr>
<td>- Continuous support of the rails</td>
<td></td>
</tr>
<tr>
<td>- Virtually maintenance-free, including less rail corrugation, if well constructed</td>
<td></td>
</tr>
<tr>
<td><strong>Extra pros and cons for Madrid Metro environment</strong></td>
<td></td>
</tr>
<tr>
<td>- Tunnel provides excellent support</td>
<td>- Mechanised construction with a paver is probably infeasible; other methods have to be found</td>
</tr>
<tr>
<td>- Construction conditions can be controlled</td>
<td></td>
</tr>
<tr>
<td>much better than in the open air</td>
<td></td>
</tr>
</tbody>
</table>
Analysis of the track maintenance process
An analysis of the maintenance conditions on the existing Madrid Metro network was subsequently performed because the local conditions would largely determine the quality of the track (installation) and the maintenance needs – e.g. the quantity of track in the curves. A design principle for the new lines was that all curve radii must be larger than 250 metres, which would result in maintenance levels fairly similar to tangent track. As Table D.4 shows, much smaller radii are found on the existing network, which means that the M&R data for the new lines would diverge from the existing network; these differences needed to be filtered out.

Table D.4: Alignments found at the Madrid Metro network in 1998

<table>
<thead>
<tr>
<th>Radius</th>
<th>Quantity of track</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>less than 200 metres</td>
<td>27,058 metres</td>
<td>11.19%</td>
</tr>
<tr>
<td>between 200 and 300 metres</td>
<td>24,976 metres</td>
<td>10.32%</td>
</tr>
<tr>
<td>Between 300 and 1,000 metres</td>
<td>45,558 metres</td>
<td>18.83%</td>
</tr>
<tr>
<td>More than 1,000 metres / straight</td>
<td>144,348 metres</td>
<td>59.66%</td>
</tr>
</tbody>
</table>

Some other predictors for the initial quality and maintenance needs of the Madrid Metro tracks are summarised in Table D.5. Some changes had occurred in these factors over time. For example, in contrast to earlier applications, the accuracy of construction had improved. A disadvantage of the Edilon block track was that, up to 1998, switches were still installed in a ballast bed, causing a transition in track elasticity.69 A disadvantage of the block track design is the distance between blocks of one metre, instead of the regular 60-centimetre sleeper distance, which would cause more exchange of rail parts.

Table D.5: Important factors for estimating quality degradation on the new lines

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Indication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport loads</td>
<td>Homogeneous speeds and axle-loads, no cant deficiencies</td>
</tr>
<tr>
<td>Subgrade conditions</td>
<td>Stable concrete substructure (tunnel floor) and temperature.</td>
</tr>
<tr>
<td>Physical conditions</td>
<td>Conditions in the tunnels are controlled.</td>
</tr>
<tr>
<td>Curvature</td>
<td>Curve radii larger than 250 metres; facilities such as lubricating pumps are hardly needed.</td>
</tr>
<tr>
<td>Accuracy of construction</td>
<td>Third party audits are used for quality control</td>
</tr>
<tr>
<td>Rail type</td>
<td>UIC54 rails for the new lines. Pandrol fasteners and Edilon Corkelast are used for block track. Switches were still laid in ballast in 1998. Timber sleepers and crushed stone are used for ballasted track.</td>
</tr>
<tr>
<td>Sleeper/fastening type</td>
<td>Specialised welding teams are used.</td>
</tr>
<tr>
<td>Ballast type</td>
<td>Mostly manual spot tamping with a small machine.</td>
</tr>
<tr>
<td>Welding process</td>
<td>Both block and ballasted track have discontinuous rail support:</td>
</tr>
<tr>
<td>Tamping</td>
<td>element distance varies from 0.60 to 1.00 metres</td>
</tr>
<tr>
<td>Type of support</td>
<td></td>
</tr>
</tbody>
</table>

Three types of activities are performed in the track maintenance process, i.e. inspections (Code 1.12), preventive major M&R (Code 2.12), and corrective maintenance (Code 3.12). All maintenance tasks, with a possible exception for Code 2.12 works, are performed during the night. The usual procedure is to plan maintenance through visual inspection (patrols at night), acceleration measurements with equipment installed in trains, and inspection car campaigns measuring rail profiles and track geometry. Regular cycles are

69 Since 1998, switches have been installed on a concrete bed, using timber sleepers with Corkelast attached, or using concrete sleepers with microcellular pads; this has become the standard method.
used for each of the inspection tasks. Examples are: inspection of lubricating pumps once every month; rail profile and corrugation measurements once every year; rail wear measurements once every two years; and switch revisions once every four years.

The important consequence of the regime of nightly maintenance is an inefficient use of resources, both in terms of personnel and machines. Firstly, maintenance can seldom be organised in major operations. In contrast to the cyclical quality with clear M&R cycles found at railway companies, spot maintenance is far more common. For example, sleepers are replaced individually, and this results in a different quality pattern: replacing one sleeper has no effect on the quality of an entire track section; it only prevents the quality from dropping below the acceptable level. The effective working time for the minor maintenance tasks was only 2 hours and 45 minutes on average, while track workers were paid for a full night. Table D.6 summarises a number of important tasks that were implemented during the year 1997; more detailed data is available in the Annual Reports of the Maintenance Department.

<table>
<thead>
<tr>
<th>Code</th>
<th>Activity</th>
<th>Units of performed work</th>
<th>Paid hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.12.5</td>
<td>Geometry inspection</td>
<td>203,470 metres of track</td>
<td>273</td>
</tr>
<tr>
<td>1.12.9</td>
<td>Visual inspection</td>
<td>1,186 inspections</td>
<td>16,569</td>
</tr>
<tr>
<td>3.12.1</td>
<td>Repair fasteners on ballasted track</td>
<td>1,129 sleepers</td>
<td>1,141</td>
</tr>
<tr>
<td>3.12.2</td>
<td>Reprofiling ballast bed</td>
<td>13,577 metres of track</td>
<td>3,744</td>
</tr>
<tr>
<td>3.12.4</td>
<td>Cleaning drains of ballasted track</td>
<td>414 metres of track</td>
<td>1,723</td>
</tr>
<tr>
<td>3.12.5</td>
<td>Spot tamping</td>
<td>902 points</td>
<td>3,743</td>
</tr>
<tr>
<td>3.12.6</td>
<td>Repair fasteners on block track</td>
<td>1,608 metres of track</td>
<td>2,407</td>
</tr>
<tr>
<td>3.12.19</td>
<td>Rail replacement</td>
<td>323.60 metres of rail</td>
<td>2,012</td>
</tr>
<tr>
<td>3.12.20</td>
<td>Replacement or repair of sleepers</td>
<td>146 sleepers</td>
<td>1,768</td>
</tr>
<tr>
<td>3.12.25</td>
<td>Cleaning drains of block track</td>
<td>3,232 metres of track</td>
<td>1,526</td>
</tr>
<tr>
<td>3.12.27</td>
<td>Revision and repair of switches</td>
<td>25 switches</td>
<td>4,895</td>
</tr>
<tr>
<td>3.12.31</td>
<td>Replacement or repair of blocks</td>
<td>31 blocks</td>
<td>1,238</td>
</tr>
<tr>
<td>3.12.37</td>
<td>Removal of corrugation (grinding)</td>
<td>13,087 metres of track</td>
<td>1,428</td>
</tr>
<tr>
<td>3.12.40</td>
<td>Inspection/repair of insulated joints</td>
<td>272 joints</td>
<td>1,021</td>
</tr>
<tr>
<td>3.12.43</td>
<td>Repair of parts of switches</td>
<td>112 switches</td>
<td>3,713</td>
</tr>
</tbody>
</table>

Life-cycle cost assessment
Considering the maintenance situation of Madrid Metro, the focus of the life-cycle cost estimation had to be on analysing and estimating inspection and minor maintenance work; this is why the DSS design had to be directly modified. A DSS version was developed that could deal in more detail with inspection and spot maintenance tasks, e.g. data related to labour productivity rates, average labour costs per night hour, and average numbers of staff needed for specific inspection and maintenance tasks could be used as input. Costs relating to mechanised equipment and overhead costs were not included, as data was not available and the marginal machine costs were expected to be low; machines, already acquired for the existing network, could also be used on the new lines. Instead of estimating frequencies of periodic M&R work, the average annual amounts of inspection and small maintenance were estimated for each of the distinguished tasks. A year in which the specific task would be first performed on the new lines could be included.

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70 Machine and overhead costs can only be arbitrarily assigned to a specific line, as one machine is usually acquired for the network. However, it was clear that fewer machine hours were needed for block track.
The Airport Line to Barajas and particularly Contract 14, with a length of 5.44 kilometres, was used for the calculations. The costs of the construction process and physical track layouts were readily available, and little uncertainty existed with respect to the traffic load to be expected; the timetable would be similar to existing lines. Retrieving required maintenance data and developing maintenance expectations would, however, take several weeks.

A number of problems had to be resolved while developing forecasts of the maintenance needs for the new line. A first issue was that the historic maintenance quantities, recorded in annual reports by the Maintenance Department since 1975, showed a large variance over the years for some activities. The cause proved to be that the work definitions of some activities had changed, and that work methods and track systems had changed slightly over time.

A second problem appeared after a first estimation had been made with the available data; this showed that annual reports were not complete in showing the M&R data. Although the data used were aggregates for all block tracks, the outcome deviated considerably from the expectations gained from the qualitative analysis; the reduction in M&R for block tracks was found to be very small. After investigation and interviews with Metro staff members, major M&R works were found labelled as 'investments' and 'outsourced work' and were not included in the annual reports. The issue was resolved by asking the Metro staff to provide information on the M&R projects being performed over time. Any ballast renewal or cleaning had not been found over such a long period, while figures for cleaning drains in ballasted tracks were unexpectedly low. Combining these facts, a maintenance backlog was suspected and actually confirmed by maintenance staff. It was decided not to modify the figures because of the difficulty of estimating this gap; this meant that the outcome for block track would be more favourable than was estimated.

A final problem proved to be the limited preciseness of the data. Productivity figures could be derived from annual reports, but data on the amounts of maintenance were less precise with regard to the specific track systems in use. Although annual reports provided detailed data, the data proved to be difficult to use for our purpose. An example is that the numbers of total replacement blocks for all block track types were available, but that they were not specified, for example, according to the different types of block track and fastening systems, the differences in track layout (e.g. narrow curves), and the age of the track. All such data could have been easily monitored if the location where a certain task was performed had been included; it was clear that the sole purpose of the administration system was to account for the labour hours involved and demonstrate overall financial needs.

Considering the data problems it was decided to directly involve the Madrid Metro maintenance personnel in the forecasting of M&R needs; however, it was decided to continue with developing a 'conservative estimate' for the Edilon block track, compared to ballasted track. Maintenance quantities were based on historic data from 1975-1997; modifications through expert judgements were only allowed on the basis of solid facts, such as data on curves, and a rough consideration of the age distribution of tracks on the existing network (see Table D.7). No changes were made to the data on block tracks, despite the acknowledged fact that the quality of the systems had increased significantly since the introduction in the 1970s,
when rigid blocks were used. The Madrid Metro staff suggested that only a few blocks of the Edilon system had been replaced or were expected to need replacement. Following this approach, the data was developed and audited with assistance from the maintenance staff and the Comunidad. Although some question marks remained, both on the side of the ballasted and the block track (e.g. rail parts renewal), it was considered an appropriate estimation basis.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Ballast track</th>
<th>Block track</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grinding for elimination of corrugation</td>
<td>27.60</td>
<td>45.54</td>
<td>metres of track</td>
</tr>
<tr>
<td>Replacement of continuous welded rail</td>
<td>44.28</td>
<td>44.28</td>
<td>metres of rail</td>
</tr>
<tr>
<td>Replacement of sleepers / blocks</td>
<td>43.07</td>
<td>0.36</td>
<td>sleepers / blocks</td>
</tr>
<tr>
<td>Repair of fasteners</td>
<td>8.15</td>
<td>21.88</td>
<td>fastening clips</td>
</tr>
<tr>
<td>Reprofiling ballast bed</td>
<td>50.18</td>
<td>-</td>
<td>metres of track</td>
</tr>
<tr>
<td>Spot levelling and tamping</td>
<td>4.20</td>
<td>-</td>
<td>spots</td>
</tr>
<tr>
<td>Cleaning drains</td>
<td>6.27</td>
<td>35.25</td>
<td>metres of track</td>
</tr>
</tbody>
</table>

It was agreed with the Comunidad to estimate the life-cycle costs for a time horizon of 50 years and using a real interest of 5%. Further, the construction costs for a round, bored tunnel were used; the present value of the costs after that period would be practically negligible. With these standard settings, the Edilon block track proved to be at least 10% less expensive than ballasted track (see Table D.8). The costs for flattening the tunnel floor were included; in the case of a bored tunnel, more supporting concrete is needed. Inspection and maintenance makes up a considerable part of the discounted life-cycle costs of ballasted track (37%), compared to block track (21%).

<table>
<thead>
<tr>
<th>Track structure</th>
<th>Construction</th>
<th>Inspection</th>
<th>Maintenance</th>
<th>Life cycle costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballasted track</td>
<td>690 euros</td>
<td>40 euros</td>
<td>364 euros</td>
<td>1,094 euros</td>
</tr>
<tr>
<td>Edilon blocks</td>
<td>775 euros (12%)</td>
<td>31 euros (78%)</td>
<td>177 euros (49%)</td>
<td>983 euros (90%)</td>
</tr>
</tbody>
</table>

Considering the fact that conservative data had been used for block track and that some maintenance backlogs for ballasted track had been neglected, everyone involved was convinced of the trustworthiness of the assumptions and the probability of the outcomes. Some uncertainties needed to be resolved, and a scenario analysis was considered as a useful, final approach for those. Table D.9 lists a few uncertainties, including the initial, incorrect output, which excluded the larger M&R works. First, the model was also run with different interest rates. The interest scenarios showed that the lower the interest rate, the more positive the outcome for block track would become; this is because the impact of interest on the construction cost was significant. Scenario 4 concludes that the compound interest effect erases much of the expenditures made after 50 years. Scenario 5 shows that the results remain valid for construction in a conventional tunnel; concrete is saved in the ballasted track alternative, but this saving is small. Finally, uncertainty with respect to rail and block renewal was analysed. The lack of precise data on rail parts replacement could be a risk, but the Metro staff stated that there was no notable difference. This was confirmed by the technical research undertaken by Delft University, which indicated that, although ballasted track behaves more favourably in many wheel/rail aspects, the impacts would not be that significant [Esveld et al., 1998]. Further, an analysis showed that using the block track system instead of ballasted
track, would be break-even if five blocks per kilometre had to be replaced each year of the period in question, which was unlikely considering past performance and current state.

Table D.9: Estimated life-cycle costs per metre of track for a few scenarios (indicative)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Ballasted track</th>
<th>Edilon block system</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data Annual Reports 1995-1997 excluding 'investments' (code 2.12)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Standard settings (5%, 50 years)</strong></td>
<td>1,094 euros</td>
<td>983 euros</td>
</tr>
<tr>
<td>1) Discount rate 0%</td>
<td>1,795 euros</td>
<td>1,345 euros</td>
</tr>
<tr>
<td>2) Discount rate 3%</td>
<td>1,259 euros</td>
<td>1,069 euros</td>
</tr>
<tr>
<td>3) Period of analysis 25 years (5%)</td>
<td>1,002 euros</td>
<td>935 euros</td>
</tr>
<tr>
<td>4) Period of analysis 100 years (5%)</td>
<td>1,129 euros</td>
<td>1,001 euros</td>
</tr>
<tr>
<td>5) Track in conventional tunnel</td>
<td>928 euros</td>
<td>838 euros</td>
</tr>
</tbody>
</table>

Presentation of results to the Comunidad and the Madrid Metro

In July 1998 everyone involved in the analysis process, plus a number of outsiders, discussed the final report of the entire research programme in Madrid. The combined results from the technical and financial studies provided confidence in Madrid Metro's initial choice of Edilon block track. In return for a relatively small extra investment of 12%, reduced maintenance costs of more than 50% could be expected; reduced production costs were clearly the key to this success. It was expected that the uniform application of block track on the new lines would provide more for efficiency opportunities in the inspection and maintenance regime. The Comunidad retained its choice of Edilon block track. N.B.: an independent research project by the University of La Coruña confirmed several findings of the research by Delft University [Bugarin et al., 1999]. Although there was still some element of uncertainty in the estimations, risks had been well considered and presented, according to the Comunidad.

Important recommendations were made to improve the system for collecting track quality and maintenance data in order to improve the quality of decision-making in the future. Most data was being registered to justify paid hours and not to make them suitable for improving the maintenance concepts. One of the recommendations was that a computerised database should be developed, which could relate figures on traffic, performed M&R and inspections to specific components and homogeneous track segments. The new extensions would provide an opportunity to start collecting accurate data from the first operating day onwards.
E: Railway track renewal and upgrading up to the 1990s

Track maintenance and renewal was treated differently before the reorganisations which have taken place since the mid-1990s. Under the state-owned Netherlands Railways (NS), track renewal was in the hands of a central ‘review team’ of Section IS8 (known previously as WW4) of the NS Infrastructure Services Division. Maintenance districts, which were not identical to today’s Regions, received a certain budget for maintenance, while they needed permission from the central review team for track renewals. For maintenance, a system was developed to roughly verify and compare budget levels between the districts, based on so-called ‘fictive maintenance units’, which included factors such as subsoil quality, number of switches, and average traffic load [NS, 1990]. For renewals, the IS8 review team visited the districts to inspect sections prepared for renewal. If their ‘carpenter’s eye’ considered renewal necessary then budget was granted to the district, otherwise the renewal had to be postponed. The available funding for track renewal was not granted on a yearly basis, which meant that the available budget need not be used (entirely) in the particular budget year - unlike today’s cash system; IS8 could decide to perform renewals earlier or later. An accounting system existed, which kept track of the renewal plans and made sure that the fund was used correctly.

IS8 thus had responsibility to develop a central policy for track renewal. This was achieved by developing so-called ‘goal maps’, which provided a detailed outlook of the track systems to be installed on each transport corridor. The aim was mainly to arrive at an optimal track structure, ‘considering the needs of the market and the costs of maintenance and renewal’ [NS, 1988]. It basically meant introducing a heavier track structure in order to allow internationally defined D4 traffic, i.e. passenger trains with speeds up to 160 km/h and locomotive axle loads of 21 tons, and freight trains with speeds up to 100 km/h and axle loads of 22.5 tons. Practically all scenarios elaborated on the introduction of continuously welded UIC54 rails throughout the network with either concrete sleepers, in ballast beds of at least 25 cm of crushed stone, or hardwood sleepers with inclined standard baseplates. Track systems with softwood sleepers, the old NP46 rail type, and the so-called Nefit fastenings were already considered outdated at the end of the 1980s. These existing systems would be maintained as usual and replaced when they were too degraded. IS8 also kept track of realised lifespans, and developed a table of ‘theoretical lifespans’ expected for each type of track.

These goal maps and ‘theoretical lifespans’ were included in a ‘Policy Document’ in 1988 [NS, 1988], which also included a few rules of thumb with respect to choices to be made in the maintenance planning process. However, clear advice on the choice between partial or full track renewal was not provided; precise merits should be judged within the context of each individual case, e.g. the realisation of a more homogenous quality of adjacent track sections and the possible reuse of components on side tracks. The document also stated that more attention should be given to developing life-extending M&R solutions; this was followed by a study, in Dutch known as ‘Snoeien om te groeien’, to reduce the renewal budget by 10% through life-extending maintenance. During the 1990s, two smaller policy documents were published to update the 1998 Policy Document. A significant change was the decision to also install mono-block concrete sleepers on peripheral lines [NS, 1993; NS, 1994]. After the reorganisations that started halfway through the 1990s, IS8 and its central review team disappeared.
F: Outcomes of the LCM+ pilots

This appendix provides a brief outline of the pilots performed. Details with respect to track possessions and sensitivity analysis have been left out, but general findings are briefly mentioned in the text. Some instruction is needed for the charts included on the following pages. Major renewals during the first 50 years are labelled as ‘investments’, while all other works, including life-extending works, are labelled as ‘maintenance’. The charts present the annuity of each alternative, which is the annual cost of depreciation and interest that results from the particular decision alternative; costs of possessions are based on the most recent penalty rates, as applied by ProRail. Absolute outcomes between the pilots are not fully comparable, because only costs influenced by the particular alternatives have been included (for a few cases). Finally, note that possession costs concern planned possessions in the case of track renewals, whereas they concern unplanned possessions (due to failure) in the case of switch renewals.

F.1 Theme ‘Life extension and scaling up of work methods’

The Sittard-Heerlen pilot

This line section is a branch of the Amsterdam-Maastricht corridor, which is practically only used for destination traffic to the town of Heerlen. It has an annual gross tonnage of 4.6 million tons, calculated according to UIC leaflet 7.14, which means that it is a UIC Class 5 line. The route has been assigned a transport value of 3, which means that it is of moderate importance; ProRail assigns the least important routes a value of 1, while the most important routes are graded a 6. Since there is no freight traffic, tracks are available for maintenance during the night (5 hours during the week and 7 hours at weekends).

The track section consists of around 5 km of NP46 track; although NP46 refers only to the rail type, sleepers and fastenings have also been made fit the installation of NP46. Of this section, 4 km is continuously welded rail (CWR), of which 3250 m are on hardwood sleepers dating from 1970, and 700 m are on softwood sleepers; 1 km is in a curve and consists of jointed rail on hardwood sleepers.

Ballast bed and, most of all, sleepers and fastenings are in a degraded state along the entire section; replacements and improvements to the individual baseplates and clips were made in 1997, but practically all fastenings were expected to be worn-out in 2002. Considering the state of the track, a full track renewal and upgrading to UIC54 rails with concrete mono-block sleepers was planned. The Region South proposed the following solutions:

1. Preservation of the NP46 track system. New hardwood sleepers and a new ballast bed should be placed; all rails to be continuously welded.
2. Preservation of the NP46 track system, but using existing sleepers (further referred to as reusable sleepers; these sleepers are available from another location on the network, thanks to upgrading works).
3. Installation of UIC54 rails with concrete sleepers through a full track renewal. This was the solution included in the preliminary production plan for 2002.
4. Solution 1 is not performed in 2002, but postponed until 2007 by large-scale maintenance in 2002. Softwood sleepers are replaced with hardwood, coils are screwed into the remaining sleepers and rails are made long welded.
5. Solution 2 is not performed in 2002, but postponed until 2007. Life-extending maintenance is performed in 2002, similar to Solution 4.
6. Solution 3 is not performed in 2002, but postponed until 2007. Life-extending maintenance is performed in 2002, similar to Solution 4.

The first solution would be less usual in today's railway environment and therefore more costly than it used to be, but the second solution could be realised fairly well and would not require much investment. However, a disadvantage is that a shorter lifespan of only 17 years is expected for these reusable sleepers, after which a full track renewal with UIC54 track would still be necessary. In the third solution UIC54 track is installed immediately, preventing more renewals over the next 50 years. The last three solutions make a postponement of the renewal possible.

Two preferable solutions were found (see Figure F.1 for the outcomes). Solution 3 scored best in terms of possession time, while Solution 6, the 'coils solution', scored best in terms of costs of ownership; the outcome was assessed to be rather robust. In 2001 the region chose to elaborate Solution 6 further, because the local situation allowed free access during the night and the solution could be implemented in short time windows - Solution 3 was adopted after all in 2002 (see Section 6.7). The 'coils' solution can serve as an instrument to level out investments in renewals and allocate budget to more critical line sections.

<table>
<thead>
<tr>
<th>SOL: Full renewal in 2002</th>
<th>SOL: Life extension coils, next SOL.1</th>
<th>SOL: Life extension coils, next SOL.2</th>
<th>SOL: Life extension coils, next SOL.3</th>
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<td>Sittard-Heeren</td>
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<td>Figure F.1: Estimated life-cycle costs 2000-2050 for Sittard-Heeren (as of 2001)</td>
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The Assen-Haren pilot

This line section is part of the route from Utrecht, via the town of Zwolle, to Groningen. Traffic is limited to around 9 million tons per year (UIC Class 4); it has a transport value of 3. About 8 km of relatively new Nefit track (installed in 1978) needs to be renewed, according to the national Nefit policy. The tracks have a long maintenance history, including mud-pumping spots and broken or loosened fastening clips. Many clips had been replaced by so-called 'Veldermans', a solution developed especially for Nefit-tracks.

Within the framework of LCM+, the Region Northeast was asked to develop and assess several solutions that would result in removing the Nefit clips within a period of 5 years. The region proposed the following solutions:

1. Installation of UIC54 rails on concrete sleepers with new ballast. This was the solution included in the preliminary production plan for 2002.
2. Renewal of ballast bed and sleepers only (also referred to as partial track renewal). The fairly new UIC54 rails are reused; their residual life would be at least 20 years.
3. Solution 1 is not performed in 2002, but postponed until 2007. A large-scale maintenance action, involving the use of Veldermans on around 60% of the fastenings in 2002 guarantees track functionality in the meantime.
4. Solution 2 is not performed in 2002, but postponed until 2007. Life-extending maintenance is performed in 2002, similar to Solution 3.

![Figure F.2: Estimated life-cycle costs 2000-2050 for Assen-Haren](image-url)
Figure F.2 shows that the large-scale installation of Veldermans proposed in the last two solutions results only in a small cost saving. The savings are only substantial if this postponement spans 10 years (see bar on the right). It also requires more work shifts in a relatively short period of time. This solution was therefore not desirable, although it could serve as an emergency measure. The region opted for Solution 2; the expected possession time over a period of 50 years was even lower, since feasible lifespans were utilised as much as possible.

The Leeuwarden-Stavoren pilot

This pilot concerns a track section of around 7 km, which is part of the UIC Class 6 line from Leeuwarden to the town of Stavoren and carries 1.3 million tons per year. Two trains per hour are operated during daytime hours (four in peak hours). The tracks still consist of jointed rails, 6 km of straight track (renewed with reusable sleepers in 1980) and 1 km of curved track (renewed in 1976). Both sleepers and the rails at the fishplate joints were worn out; installing continuous welded rail (CWR) on the curved track was not allowed on the installed baseplates for safety reasons. The region proposed the following set of alternatives:

1. Installation of UIC54 rails with concrete sleepers (standard sleeper distance) and new ballast. This was the solution included in the production plan for 2002.
2. Installation of UIC54 rails with a sleeper distance of 75 cm.
3. Installation of UIC54 rails with a sleeper distance of 75 cm. In addition, the renewal of the curved track is postponed by 5 years. The quality of the rails is maintained to an acceptable level by a large-scale exchange of rail parts.
4. Solution 2 is not performed in 2002, but postponed until 2007. New rail parts are installed on 50% of the joints, either manually or using a flash-butt welding machine.
5. Solution 2 is performed in 2002 using reusable UIC54 rails from another location.

In all solutions, the new track system is laid on a ballast bed with a height of 20 cm measured from the bottom of the sleepers, instead of 30 cm for heavier lines. With the exception of Solution 1, all solutions use a wider sleeper distance, considered feasible because of the light loads on the track. A disadvantage of the third solution is the separate renewal of the curved track section, which results in higher unit costs as well as more geometric maintenance for a couple of years. Figure F.3 on the next page shows the outcomes. Solution 2 and particularly Solution 5 (with the lighter track design) scored best and were found to be rather robust, despite their somewhat shorter lifespan. Finally, postponing renewal was not found to be desirable, even if 10 years were feasible. The region preferred to perform the fifth solution, which emerged in the last month of the project. There are currently several reasons for reviewing the validity of the assumptions underlying this solution (see below and Section 6.7).
Figure F.3: Estimated life-cycle costs 2000-2050 for Leeuwarden-Stavoren (as of 2003)

N.B.: note that an error was made in the input data used for Solution 5, which was only found out after the pilot had been realised. Rail renewal, needed due to the installation of reusable rails, was accidentally excluded, which meant that savings of 20% were forecast instead of the 10% now depicted in Figure F.3. The solution did not pass through the regular data validation process, as was the case with all other pilots and solutions; clearly, the author should have organised this data validation better and is therefore partly responsible.

The Alphen-Leiden pilot
The line between the towns of Leiden and Alphen aan den Rijn is located in the Randstad (the Rimcity) and connects Leiden to Gouda and Utrecht. The line carries 8.3 million tons per annum (Class 4) and has a transport value of 2, as it does not belong to the core network. The double-track sections carry only half the traffic and belong therefore to Class 5. Around 6 hours are available for night-time maintenance.

The pilot concerns around 14 km of line, of which 12 km is Nefit track that was installed between 1978 and 1984. The Nefit track is part of a patchwork with other track types, installed over lengths of approximately 200 metres and some having residual lives up to 15 years. The Region Rimcity South suggested the following solutions:
1. Renewal of the Nefit track segments only during possessions of 6 or 9 hours.
2. Renewal of all track segments during possessions of 6 or 9 hours.
Both strategies would employ a renewal train and partial renewal (ballast and sleepers); residual life of the rails was estimated to be at least 25 years and more than 30 years for many segments. Unit costs increase significantly for the renewal of separate segments, partly due to an inefficient use of M&R slots. An advantage is that several track segments can be renewed much later. In the further analysis, a 9-hour slot for renewal was taken as the starting point. As Figure F.4 on the next page shows, the difference in outcome between clustered or unclustered renewal was minor, which is why the Region Rimcity South chose the clustered renewal. A possible reuse of components ('cascading') was left to the discretion of the region.

Analysis of long single-track possessions (across the pilots)
The LCM+ core team considered it important to link up with discussions within ProRail on longer, single-track possessions. The regions were asked to submit their expectations on probable unit costs for slots in the order of 40 to 100 hours. After discussions in January 2001, it was decided to base the estimations on cautious assumptions on productivity gains; the unit cost for stretches over 5 km was estimated to be around 15% lower for possessions of approximately 40 hours. For larger renewals of about 100 hours, the benefits would also depend on whether or not new and old ballast needed to be transported from the site, because this would cause some time losses. Overall life-cycle cost savings of 5-10%, including the costs of track possessions, were considered realistic. Figure 6.9 shows the Alphen-Leiden pilot as an example.

![Figure F.4: Estimated life-cycle costs 2000-2050 for Alphen-Leiden](image-url)
F.2 Theme ‘Functionality-based design and instant reuse of components’

The Amsterdam Switches pilot

This pilot studied the renewal of switch no. 1107A at the Watergraafsmeer yard, which is used for passenger train operations to and from Amsterdam; it concerned an ex-post evaluation of a decision that had been made in 2000. Switch 1107A ultimately needed to be replaced in 2003; however, thanks to the monitoring of the upgrading plans around Amsterdam Central Station, the TR planners had discovered that main-track switch no. 237 would become available in 2000. They assessed the residual life of this switch on a side-track location to be at least 20 years and decided to re-use it. The region was asked to make this decision process available for review. They came up with the following solutions:

1. A new 1:9 switch on timber sleepers is installed in 2003. This is the reference situation; reusing components was abandoned after the Regeneration Depot was closed down during NS restructuring. Switch 237 is sold as scrap.
2. Switch 237 is immediately transported to the yard and installed in 2000. In this solution it is assumed that another reusable switch is found in 2020 and 2040, i.e. the principle of reusing main-track switches can be continued.
3. Switch 237, with a lifespan of 20 years, is installed in 2000. In this solution it is assumed that a new switch will have to be installed in 2020.
4. Switch renewal is postponed until 2015 through restoration and replacement of components. Half the ballast and sleepers need to be replaced in 2003, the other half in 2011; other switch parts are also revised in these years.
5. Solution 4 is performed, but all ballast is replaced in 2003.

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![Figure F.5: Estimated life-cycle costs 2000-2050 for the Watergraafsmeer switch](image)
Figure F.5 on the previous page shows that instant reuse (Solutions 2 and 3) considerably reduce life-cycle costs – by 15-30% depending on whether the reuse principle can be continued in the future. The fourth and fifth solution employ life-extending maintenance, which have proven to be effective for hardly used side tracks; however, the Watergraafsmeer yard is used frequently, which is why this receives a poor score. Solution 5 achieves a small reduction in the ongoing maintenance, compared to Solution 4. The Expert Panel concluded that the reuse principle could be highly effective; possession time was not expected to be a major obstacle for the yard.

The Eindhoven Switches pilot

The Region South chose to explore the boundaries of the ‘reuse principle’ applied in the Amsterdam switch project. The pilot was therefore set up under a number of ‘negative’ assumptions. The hypothetical side track would be located in one of the industrial areas, belonging to UIC Class 6. The main-line switch at Eindhoven station would only have a residual lifespan of 10 years. Finally, the switch renewal would not be coordinated with the Construction Division, which is why the Preservation Division needs to arrange resources for transport and installation itself. The following solutions were analysed:

2. A reusable switch with a lifespan of 10 years is transported from the Eindhoven yard to the particular side track.
3. Solution 2 is performed, but the switch is saved in a stock depot for 1 year before a suitable location becomes available.
4. A switch with a 10-year lifespan is reconstructed from reusable, off-the-shelf switch parts.

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Figure F.6: Estimated life-cycle costs 2000-2050 for the hypothetical side-track switch
Figure F.6 on the previous page shows that any type of reuse under these conditions would not be recommendable. The only cost savings, i.e. lower acquisition costs, are not enough. Note that both Solutions 3 and 4 have to be considered as theoretical exercises, because fact-based cost data for keeping a switch or switch parts in stock was not available. In the third solution some costs are attributed for storing and preserving the switch for 1 year.

The Meppel Switches pilot

The planned renewal of switches 269, 271A, 271B and 277 in 2002 at Meppel station (a town in the Region Northeast) raised the question as to which design to apply for the switches. A new switch on timber sleepers would have an expected lifespan of only 25 years at this particular location. In recent years the regions have been asked to use switches on concrete sleepers as much as possible, mainly since they have longer lifespans. A central department recently suggested that a switch on concrete sleepers with a moveable switch frog, instead of a fixed frog, would also be more favourable in terms of life-cycle costs. Moveable frogs cause less friction when trains use the switch, but they are more expensive to acquire and install.

Controversy on the claimed cost-effectiveness was the main reason for asking the regions about their expectations. The Region Northeast, which performed the pilot, suggested the following decision options:

1. A new 1:9 switch on timber sleepers, with a fixed frog, is installed. The point mechanism of the old switch can be reused.
2. A new 1:9 switch on concrete sleepers is installed with a fixed frog.
3. A new 1:9 switch on concrete sleepers is installed with a moveable frog.

Although a switch on concrete sleepers is increasingly common, the construction costs are still higher, but its expected service life is 40 years, rather than 25, and the reduced maintenance requirements are important improvements. But the switch frog still needs to be replaced every 8 years. In contrast, the third solution is expected to realise a frog lifespan of 25 years and switch lifespan of 50 years. Initial investment is almost 40% higher, since changes are also required in the switch heating equipment.

The analysis showed that switches on concrete sleepers with fixed frogs are estimated to have 5% lower life-cycle costs at moderately used yards such as Meppel (see Figure F.7 on the next page); the main reason being that twice as many failures are expected, since an extra moveable element is added to the switch design. Costs of traffic disruption are included. On the other hand, less planned possession time is needed in the third solution; though this is not considered a critical factor since there are sufficient opportunities for M&R work at the yard. The second solution is much more robust although life expectancy is reduced by 20%, which would imply that it could also be cost-effective under higher loading. It was concluded that a fixed frog is still the only correct choice, except for high speeds and situations where noise abatement is crucial.

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71 A frog is the steel triangle, where ‘the two tracks in the switch meet’.
The Baarn-Amersfoort pilot

The pilot aimed to study the potential impacts of combining two projects that were included individually in the preliminary production plan for 2002. This concerned a main-line Nefit renewal between the towns of Baarn and Amersfoort and renewing sleepers at the nearby yard at Amersfoort. Both cases concerned about 6 km of track. The Baarn-Amersfoort section of the line is part of the core rail network and is used quite intensively for passenger traffic (transport value of 5); it carries an annual tonnage of 13 million gross tons (UIC Class 3). A quality check confirmed that sleepers and rails were in good condition, which is why the Region Rimcity North recommended giving the components a second lease of life at the yard. However, the sleepers were designed for UIC54 rails, whereas NP46 track was used at the yard. The following reuse solutions were elaborated (labelled with a Y for ‘yard’):

Y1. New sleepers are used (standard solution). A potential problem is that new (timber) sleepers, fit for use with NP46 rails, might not be available and this would also require new rails or a solution as proposed in Y2. Extra costs that could result from this problem were not included in the estimate.

Y2. The timber Nefit sleepers from Baarn-Amersfoort are installed at the yard, using so-called ‘chocolates’, i.e. cast-iron strips to fill the gaps. This solution was put forward as a safe solution for these sidings.

Y3. The Nefit sleepers from Baarn-Amersfoort are renovated with NP46 baseplates.

Y4. Both UIC54 rails and Nefit sleepers are reused at the yard.

The solutions distinguished for the main line renewal were (labelled with M):
M1. Full track renewal using the 'sections method': the ballast bed is renewed and UIC54 rails and concrete sleepers are installed using the sections method. This solution is added to compare it with the use of renewal trains.

M2. Full track renewal with renewal trains. This was the solution included in the preliminary production plan for 2002.

M3. Partial track renewal: ballast bed and sleepers are renewed, but the UIC54 rails are retained. Their residual life is estimated at 20 years on the main line.

A number of possible combinations of the Y- and M-solutions were elaborated; for example, rails can obviously not be used at the yard when they are reused on the main line. Compared to Solution Y1, the unit costs of construction for Y2, Y3, and Y4 are estimated to be respectively 55%, 20% and 20% less expensive. The technical feasibility of Y2 was first heavily debated, but the region could refer to a successful field application. Y2 would require some corrective maintenance work each year.

Figure F.8 shows the outcomes for the analysed set of solutions, which include the costs of track possessions for the main line. A partial renewal of the main track in combination with the 'chocolates' solution (M3+Y2) was estimated to reduce life-cycle costs by around 13% and would immediately reduce the investment required. The ranking of the various solutions proved to be robust under changed operating conditions and the region decided to propose M3+Y2 for the production plan.
The Instant Track Reconstruction pilot

This study concerned an investigation of the promises of heavier track designs for reducing life-cycle costs of the Dutch network; it concerned two new ballast systems i.e. the German Breitschwellen (‘wide sleeper’) and the Austrian Rahmenschwellen (‘frame sleeper’) (see Fig. F.9), plus one slab track system. The starting point was the use of usual 9-hour time slots.

Figure F.9: Breitschwellen (left) and Rahmenschwellen (right)

The limitation to consider only usual time slots would not be a problem for the ballasted systems, but would at best allow prefab slab systems; in-situ construction would consume too much time. It was decided to use the study only to analyse whether the systems had the potential to reduce life-cycle costs on the conventional network. Literature survey and supplier information provided a set of input data that sufficed for a first indication (using the setting of the Baarn-Amersfoort section). Figure F.10 shows the outcomes, which indicate that the Rahmenschwellen in particular has the potential to reduce long-term costs by 15%. A prefab slab system proved to be far too costly.

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Figure F.10: First estimate of life-cycle costs 2000-2050 for Instant Track Reconstruction
Summary


This book is the result of my research into ways of stimulating a life-cycle approach in railway design and maintenance. Two developments in the European rail environment were the main reasons for starting this research. Firstly, reforms currently taking place reveal considerable dissatisfaction by policymakers with the functioning of the railway sector. The general opinion is that railways should improve their cost structure and performance drastically, in order to become a more attractive mode of transport. A consequence is that bodies responsible for infrastructure management, further referred to as infrastructure managers (IMs), face pressures to meet increasing performance pressures (availability and reliability) for often-reduced budgets. Secondly, these IMs seem to have clear difficulties in meeting such high expectations, causing the risk of focusing too much on short-term success with counterproductive impacts. Examples are masked, deferred investments or, contrarily, excessive budget claims, which do not remove root causes of performance problems.

This study aimed to develop a ‘decision-support environment’ that provides decision makers with timely and trustworthy information on long-term system cost and performance levels for different design and maintenance strategies. This was pursued in three subsequent steps. Firstly, the changes occurring in the rail infrastructure sector and their consequences for decision making were studied in detail, in order to signal bottlenecks and needs of decision makers. Secondly, a literature search was conducted for concepts and methods that would assist in providing support to decision makers. Thirdly, the author tested the resulting decision-support approach in three real-life case studies, in order to indicate its capability to improve the quality of the decision-making. Anonymous interviews with participants in the decision-making process were held in order to enable an objective evaluation.

State-of-the-art in railway design and preservation

Interfaces that were blurred in the days of the state-owned monolithic railway company require increasing attention. This results not only from the requirement to separate infrastructure and operations management, but is also due to growing traffic demands. For example, separated transport operators are keener on having robust, ‘guaranteed’ levels of infrastructure reliability. This ‘interface management’ requirement is shown by regimes for
allocating slots and maintenance work to operators and for controlling outsourced maintenance tasks.

Clear evidence was found of the impacts of these changing requirements within construction and maintenance processes. One discovered trend was decentralisation within the IM organisation, while also introducing formal procedures and planning cycles for budgeting, maintenance planning and work scheduling. Another recent trend is the growing interest in applying systems engineering principles to the decision-making process. R&D projects show the desire by IMs to base design and preservation decisions on their eventual impacts in terms of ‘RAMSHE’ (reliability, availability, maintainability, safety, health and environmental friendliness). The development of European Standard 50126 is an illustration that prescribes procedures for testing, commissioning, monitoring and auditing. Another illustration is the gradual introduction of ‘performance payment regimes’. It can be (cautiously) concluded that railway maintenance is slowly moving from a ‘craftsmanship’ phase, in which maintainers follow rigid work instructions and (subjective) experience, to an ‘engineering’ phase, in which quantitative estimations play a more important role.

However, despite these developments, the maintenance management process on the IM ‘shop floor’ seems still at an early stage. This is particularly demonstrated by the absence of information systems and costing frameworks that are focussed on the life-cycle impacts of design and maintenance strategies.

Theory and methods of maintenance engineering

The literature made clear that maintenance has also traditionally been treated as an operational ‘art’ in several other capital-intensive industries, but that ways of approaching maintenance in a fundamental, scientific way have become available over the past few decades. The benefits of this ‘maintenance engineering’ discipline are now generally acknowledged (i.e. reduced risk of failure, extended asset lives and reduced operating costs). The literature distinguishes three phases in the evolution of the corporate maintenance function, i.e. the:

- ‘operational maintenance management’ phase, which aims to minimise maintenance costs through an efficient use of resources and materials;
- ‘maintenance engineering’ phase, which focuses on minimising maintenance and maintenance-dependent costs;
- ‘life-cycle management’ phase, which focuses on minimising life-cycle costs of all assets from the planning and acquisition phase onwards.\(^{72}\)

The centrepiece in a proactive approach to maintenance is the so-called ‘maintenance concept’, which defines the appropriate tasks and activities needed in relation to the importance of the particular assets (i.e. criticality of failures). The concept steers the maintenance planning process and is updated regularly based on new information (following a ‘Plan, Do and Check’ cycle). The concept is developed in several steps:

(1) generating maintenance strategies for individual assets;

\(^{72}\) Apart from direct maintenance costs, running life-cycle costs include costs of non-performance, financing, staffing, logistic support, energy consumption, and disposal.
(2) defining clustering rules that optimise the frequencies of activities based on scale or scope effects; and

(3) defining rules for assigning time windows to maintenance packages based on opportunities that occur in the short and medium term.

The maintenance strategies are based on the analysis of degradation and failure behaviour of each asset (type). In a life-cycle approach, maintenance engineering is used for the timely modification of asset designs. Minimised life-cycle costs are the key objective, while meeting functional specifications (e.g. system capacity and RAMSHE).

The literature reports successes with a broad set of approaches to optimise maintenance costs, performance and risks. Examples are ‘Reliability-Centred Maintenance’, ‘Total Productive Maintenance’ and ‘Life-Cycle Costing’. However, a conclusive theory on how to deploy these methods consistently in a ‘performance improvement programme’ is missing, possibly due to the variety of systems needing to be maintained. Most authors suggest the joint use of process-oriented and quantitative methods, but systematic evaluations of the usability of (combinations of) these methods are hard to find. Several authors suggest starting with a number of ‘quick wins’ to show system operators and managers the possible benefits of a systems approach. In their experience, the focus should be first on a critical portion of the total ‘asset population’ that requires quantitative analysis methods.

It was considered appropriate to base the ‘decision-support environment’ on the life-cycle costing concept, because of its focus on ‘cost drivers’ and ‘performance killers’. Although LCC requires quantitative data, it should be able to show some result in situations with poor maintenance data. In this case, ‘tacit knowledge’ within the organisation should be mobilised through expert judgements. Nevertheless, serious problems were expected with any approach, due to:

- the current state of maintenance management within the European rail sector;
- the difficulty of assessing the long-term impacts of new technologies; and
- the fact that a life-cycle approach crosses traditional organisational boundaries.

**Design and application of a supporting approach**

It was decided to explore the policy science literature in order to find ways of dealing with the organisational implications of a life-cycle approach. Two different schools of thought on public-sector decision-making were studied. In the ‘policy analysis’ school, scholars traditionally take the view that decision-making can be improved by disseminating better and timelier information to decision makers on the impacts of various strategies. Contrarily, scholars following the ‘process approach’ take the view that decision makers should focus on the interests of the stakeholders involved, because they are more willing to cooperate if their interests are served. For example, losses in one issue can be compensated by wins in other issues through ‘package deals’; a set of process rules (‘process design’) can evoke a productive process of interaction. However, over the last decade both schools have recognised problems arising from only a content- or process-driven approach. According to contemporary views, analytical support (as intended in this research) would have the best chance of influencing a participative process, i.e. involving representatives of the various
stakeholders. The concept of a decision support system (DSS) was considered a useful basis for such a process, because it provides the flexibility to answer ad-hoc questions from decision makers. A DSS for life-cycle cost analysis could be useful for:

- evaluating different physical designs or maintenance strategies (quantitatively);
- analysing impacts of restrictive conditions for construction and maintenance;
- training engineers and managers to recognise system-wide impacts of decisions.

It was decided to elaborate a theoretical model-base and implement it as a simple Excel-based prototype named LifeCycleCostPlan, which included steps for converting an expected load on the infrastructure into a life-cycle cost forecast.

In 1999, 2000 and 2001, three decision-making processes in the Netherlands were supported, with the author acting as 'DSS chauffeur'. The case studies were direct requests from managers in the field, which guaranteed a real interest in analysing life-cycle impacts. The first two took place in a consortium that planned to bid for the Infrastructure Provider Contract of the Dutch high-speed line (HSL South), while the last study took place at ProRail, which manages the conventional rail network.

The first study concerned assessing a number of candidate track systems during the Consultation Phase of the Infrastructure Provider Contract. This contract included the construction, financing and preservation of the railway system (over a period of 30 years). The potential life-cycle costs during that period were explored, which provided insights into possible cash flows, risks during the operational period and the financial consequences of the proposed performance regime. According to this regime, the future Infrastructure Provider would pre-finance the rail system construction and would be granted a ‘performance fee’ covering each quarter of the year during the operational phase. This fee would be reduced for periods of diminished performance (i.e. infrastructure reliability).

There were considerable problems with the collection of trustworthy input, while there was also much time pressure; a serious participative process, involving all partners in the consortium, was not realised. It was decided to appoint a small ‘risk analysis’ group to collect input data. In the end an unambiguous advice was not possible, because outcomes differed for the various scenarios and risk assumptions; however, it could be shown that the performance of the various track systems over the first 30 years should be fairly close.

The second case study concerned the search for a cost-effective design of the entire rail system during the Tendering Phase. During this process, known as Optimisation, the design teams for the track, signalling and power supply systems were asked to submit explicit failure and maintenance expectations. Life-cycle costs for each technical subsystem (during the period of the contract) could thus be estimated in order to discuss useful design modifications in plenary workshops. One of the largest obstacles proved to be the time needed to make the design teams aware of the importance of the process and to motivate them to develop reliability estimates.

The third case study, known at ProRail as the LCM+ (Life-Cycle Management Plus) project, concerned developing national guidelines for the planning of track renewals. The management had requested this because transparent policy rules were almost non-existent,
leading to different maintenance regions acting differently, and because peak renewal volumes were expected. An explicit objective was to base such policy rules on life-cycle cost analysis. A process was drafted that consisted of four phases: generating possible cost-saving strategies; analysing such strategies in regional pilots; developing policy rules; and developing a forecast of required track renewal volumes. The project resulted in a set of policy rules that were assessed to be cost-effective and robust. A reduction in the annual renewal volume and in life-cycle costs by at least 10% was predicted. Recommendations were also made for revising the planning process for renewals. The implementation of LCM+ started at the end of 2001, guided by the core team. Expected savings were largely realised, but the team came up against several obstacles to further improvement. The regional staff had insufficient time to analyse their plans, while the proposed revision of the planning process was not implemented.

Conclusions on the effectiveness of LCC-based support

Since the case studies concerned contemporary processes that differed significantly in context and set up, they could not be evaluated as replicable experiments. Nevertheless, important observations were possible. Decision makers in all three cases recognised and appreciated the ability of the developed approach to support the decision-making process with quantitative data. The following functions of LCC support were found:

- (in)validation of designers’ and maintainers’ ideas of system-wide impacts;
- assessment of life-cycle costs for a broad range of design and maintenance solutions;
- improved attitudes and relationships between the stakeholders involved; and
- increased commitment to life-cycle-based strategies.

However, the role and impacts of the decision support varied significantly from case to case, and all of the aforementioned functions were only realised in the last study. Also in that study, the commitment proved (yet again) to diminish to a certain extent, due to circumstances. The main conditions for the (lack of) success mentioned by the interviewees included the need for (top) management support, the type of decision (e.g. whether condition-based policies are possible), the availability of empirical data, and the way in which LCC support is provided. The conclusion is that LCC is able to influence decision-making, but that gaining commitment by stakeholders is difficult. Furthermore, the (initial) application of LCC did not lead to a shorter decision-making process. One reason is the absence of an easily accessible set of maintenance data and a ‘shared’ body of knowledge on track maintenance and renewal. Although the collection and validation of input data for new technology was very difficult, authoritative expertise on maintaining the conventional Dutch railway network was also surprisingly lacking. However, on the basis of the results found, it was expected that LCC-based support could help in starting a ‘cycle of continuous improvement’ in the maintenance policy around railway (track) maintenance and renewal; commitment to such a process seemed still lacking during the implementation of the LCM+ rules.

A number of process design principles were successful, such as including a large panel of responsible experts and developing decision alternatives by separate task groups. Finally, a crucial starting point proved to be that analyst(s) were allowed to access expertise throughout the organisation(s) and develop a transparent list of input data, which was supplied together with the outcomes. Time pressure caused by rigid or changing procedures (as during the HSL
South tender) can cause erroneous input and a chaotic decision-making process. This also means that decision makers should be supplied with realistic expectations on LCC: LCC can already be worthwhile for breaking deadlocks in the decision-making, but durable effects can only be expected in environments where learning about the long-term impacts of decisions is part of the daily work. A number of recommendations have therefore been made for further research and for infrastructure managers.

Recommendations for further research and for infrastructure managers

Firstly, topics for further LCC research have been recommended. Practitioners are advised to use the developed approach when few data sources are available; rather than developing advanced computer models, the focus should first be on developing a trustworthy data collection and validation process and gaining commitment. Further academic research into a modular DSS for estimating railway life-cycle costs is recommended in order to standardise the estimation process. Attention should be paid to degradation models, models on costs of non-performance and other social costs (e.g. noise pollution), to optimising life-cycle costs under limited budgets, and to ways of calibrating expert judgements with empirical data.

Secondly, specific areas in the design and maintenance of railway systems have been recommended for LCC applications. First of all, LCC should be applied through focused reviews of maintenance policies for entire technical subsystems. Prescribing LCC as a standard element of project proposals carries the risk of LCC becoming an instrument for having projects accepted. A minimal requirement is that experts who are not responsible for the particular projects should be involved in these studies. Apart from the track sector, such research can also be useful for other areas (such as power supply) and for decisions involving many disciplines. IMs such as ProRail should also use LCC in the pursuit of a top-down view on budget allocation between the technical disciplines and between maintenance regions based on return on investment, i.e. punctuality improvement and infrastructure durability. Budgets, certainly for track renewal, are currently still mainly the result of bottom-up funding requests, while the second study on HSL South indicated that a more analytic approach seems feasible. LCC may, for example, also be useful for studying the effects of ‘user charging’ and possession regimes for maintenance works.

Thirdly, it is advisable to research necessary organisational conditions, procedures and information systems for guaranteeing and enabling life-cycle-based decision-making, from ‘cradle to grave’, in the railway sector. Such a study could be first set up from a theoretical perspective, on the basis of the aforementioned maintenance literature and approaches. The findings could then be confronted with everyday practice, in order to identify bottlenecks and suggest ‘migration paths’. Attention in such a ‘process model’ should also be paid to ways of dealing with uncertainty in estimating life-cycle effects.

Fourthly, recommendations have been formulated for improving organisational conditions for a life-cycle approach. These conclusions stress the necessity of having a central audit or quality control team (at ProRail) that reviews realised lifespans and maintenance costs on the network, audits regional renewal proposals and proposes central yardsticks for maintenance. This team should compose statistics on lifespans, infrastructure quality and maintenance costs and, from time to time, should consult experts from outside the organisation. Timelier awarding of substantial parts of the budget to the regions might then
also be considered, in order to allow them to compose better work plans. In fact, the European rail infrastructure managers should discuss and plan this type of analysis work together in order to exchange experiences and to organise necessary technical research.

Finally, suggestions have been made regarding the institutional setting for rail infrastructure management. ‘Performance contracts’ do not seem to be a panacea for a better functioning rail sector. The Ministry of Transport should gather more insight and knowledge and ask more critical questions, e.g. regarding realised lifespans. The Ministry of Transport should also revise the current approach of funding, particularly the ‘cash’ funding for track renewal, in order to stimulate a life-cycle approach to the preservation of the Dutch rail network. Finally, it could chose to facilitate decision-making in case hurdles to a life-cycle-based design and maintenance process need to be overcome (e.g. equipment being initially more expensive than the installed base). It is expected that this recommendation is also worthwhile for other governments, although financial arrangements can vary from country to country; this expectation is based on the international investigation of Chapter 2.
Samenvatting (Summary in Dutch)


De studie heeft beoogd bij te dragen aan een instrumentarium om lange-termijn gevolgen van ontwerp- en onderhoudsvarianten in termen van eigendomskosten en infraprestatie inzichtelijk te maken, zodanig dat dit leidt tot een verbeterde besluitvorming door de infrabeheerder. Het doel was dus een beslissingsondersteunende (‘decision support’) aanpak te ontwikkelen, die besluitvormers tijdig van bruikbare, betrouwbare informatie voorziet. Een aantal onderzoeksstappen zijn hiertoe gezet. Als eerste zijn de veranderingen in de railsector in detail bestudeerd om nieuwe informatiebehoeften van de infrabeheerder te achterhalen. Vervolgens is de literatuur onderzocht op bruikbare concepten en methoden voor de ontwikkeling van de aanpak. Tenslotte is een aanpak conceptueel uitgewerkt en getoetst in drie actuele besluitvormingsprocessen in de Nederlandse rail sector. Met behulp van anonieme interviews is de werking van de aanpak in de casus onderzocht.

73 Met kosteneffectiviteit (van verschillende ontwerp- of onderhoudsopties) wordt de verhouding tussen kosten en gedefinieerde effecten, zoals bedrijfszekerheid, bedoeld. In de aanpak van dit boek dienen ontwerp- en onderhoudsalternatieven eerst aan minimumeisen (veiligheid, rijcomfort, etc.) te voldoen.
De huidige ontwerp- en onderhoudspraktijk in de spoorwegen

Het is de afgelopen jaren steeds belangrijker geworden om op de raakvlakken tussen diverse subsystemen in het Europese railvervoersysteem (bijvoorbeeld tussen technische disciplines, budgetten en gebieden c.q. regio's en landen) expliciet afspraken te maken over gewenste prestaties en functies. Dit komt zowel door de scheiding tussen infra en exploitatie, waardoor meer partijen ('actoren') verantwoordelijk zijn geworden voor onderdelen van het systeem, maar ook vanwege groeiende drukte op het railnet en verwachtingen van externe actoren. De nieuwe exploitanten vragen bijvoorbeeld duidelijker garanties op bepaalde niveaus van beschikbaarheid en bedrijfszekerheid. Voorbeelden van het noodzakelijke 'interface management' zijn expliciete afspraken of 'regimes' voor het verdelen van tijd ('slots') tussen onderhoudswerk en exploitatie en voor de bekostiging ('costing') van onderhoudswerk.


Er kan voorzichtig geconcludeerd worden dat het spoorwegonderhoud van operationeel vakmanschap, op basis van individuele kennis en kunde en historisch bepaalde technische voorzieningen, langzaam opschuift naar een 'engineering' discipline, waarbij kwantitatieve berekeningen van de effecten van onderhoud een grotere rol spelen. Deze trend uit zich ook aan de kant van de aanleverende industrie, die zich steeds meer bezig houdt met onderhoudbaarheid en onderhoudsarme ontwerpen.

Ondanks de wens om te komen tot een grotere kwaliteit van het onderhoud en een meer proactieve aanpak (d.w.z. RAMSHE effecten al meenemen vanaf de eerste plannings- en ontwerpfase) en het nodige speur- en ontwikkelingswerk, blijkt de onderhoudsbeheersing in de dagelijkse processen van de infrabeheerder nog in een prematuur stadium. Dit uit zich in de afwezigheid van informatiesystemen en -processen voor de analyse van onderhoudsprestaties, gerelateerd aan de specifieke "spoorse" objecten ('assets') en componenten, en in bekostigingsregimes die geen prikkel geven tot (optimale) life-cycle beslissingen.
Samenvatting

Theorie en methoden van onderhoudsengineering


Het uitwerken van een beslissingsondersteunende aanpak op basis van Life-Cycle Costing (LCC) leek het meest voor de hand liggend, gezien bovenstaande adviezen en gezien de huidige stand van onderhoudsmanagement in de Europese spoorwegen (gebrekkige data en een nog altijd beperkt draagvlak voor een life-cycle aanpak). Hoewel LCC kwantitatieve data nodig heeft, zou het nog redelijk bruikbaar zijn in situaties met gebrekkige onderhoudsgegevens. Via expert schattingen (‘guessimates’) kunnen aannames gedaan
worden, waarna binnen LCC modellen de gevoeligheid van de uitkomsten voor (variatie in) deze aannames onderzocht kunnen worden; onderzochte alternatieven moeten wel voldoen aan vooraf gestelde eisen. Niettemin werden grote problemen voorzien voor welke aanpak dan ook, die is gericht op ‘life-cycle management’, vanwege moeilijkheden in het schatten van lange-termijn effecten (met name van nieuwe technologie) en vanwege de stand van de praktijk.

Ontwerp en toepassing van een ondersteunende aanpak


Het concept van een ‘decision support system’ (DSS) werd beschouwd als een bruikbare basis. Een DSS is een computer-gebaseerd systeem, bestaande uit een database, een ‘model-base’ en een gebruikersinterface. Het biedt de flexibiliteit om verschillende modellen te kiezen om ad-hoc vragen van besluitvormers te ondersteunen. Van een DSS voor de analyse van levensduurkosten viel te verwachten dat het tenminste in de volgende gevallen nuttig zou zijn:

- het beoordelen van verschillende spoorontwerpen en instandhoudingsstrategieën;
- het analyseren van de effecten van beperkende ontwerp- en onderhoudscondities;
- het trainen van ontwerp- en onderhoudsstaff en hun managers in het herkennen van systeembrede effecten van individuele beslissingen.

Omdat de eisen voor een dergelijk DSS niet volledig bekend waren, werd besloten om een model-base op papier te ontwikkelen en om een eenvoudig prototype in MS Excel te ontwikkelen. De modelbase en het prototype, Life CycleCostPlan, bevatte in principe alle stappen om een verwachte belasting op de infrastructuur “om te zetten” in een verwachting van de levensduurkosten, gegeven de gekozen ontwerp- of instandhoudingsstrategie.

Drie besluitvormingsprocessen zijn ondersteund met het prototype DSS en deze auteur als ‘DSS chauffeur’. Deze casus waren directe verzoeken van managers in de Nederlandse railssector voor concrete beslissingen. Dit garandeerde dat er een oprechte interesse was voor
de analyse van life-cycle effecten. De casus moesten bovendien uitvoerbaar zijn in beperkte tijd en met zeer beperkte middelen. De eerste twee vonden plaats in een consortium dat van plan was een bod uit te brengen voor het verkrijgen van het ‘Infraprovizer’ contract van de Hogesnelheidslijn-Zuid. De Infraprovizer zou verantwoordelijk worden voor de aanleg, de financiering en de instandhouding van de hogesnelheidstracéedelen (dit laatste gedurende een periode van 25 jaar en een garantieperiode van 5 jaar). In ruil daarvoor zou deze Infraprovizer elk kwartaal een vooraf vastgestelde vergoeding krijgen, die gekort zou worden bij een te lage infraprestatie. De laatste studie werd uitgevoerd bij ProRail, toen nog de aparte taakorganisatie Railinfrabeheer, bij de afdeling Beheer & Instandhouding. ProRail is beheerder van het gehele conventionele railnet in Nederland.

De eerste studie betrof een beoordeling van verschillende spoorconstructies, die in het desbetreffende consortium kandidaat waren voor de nieuwe HSL-Zuid. De analyse van levensduurkosten werd verricht tijdens de Consultatiefase in een tijdsbestek van twee maanden. Er bleek een groot probleem met het verkrijgen van betrouwbare gegevens en er was een grote tijdsdruk. Een participatief proces, geleid door de auteur en met deelname van alle partners in het consortium, kwam niet van de grond. Er werd gekozen het verzamelen van invoerdata toe te wijzen aan een aparte ‘risicoadviseur groep’. Een eenduidig advies was uiteindelijk niet mogelijk, omdat uitkomsten verschillen voor verschillende scenario’s en aannames rond het constructieproces. De levensduurkosten van de spoorconstructies bleken wel minder van elkaar af te wijken (bij de ontwikkelde scenario’s) dan van te voren verwacht.

De tweede studie, uitgevoerd tijdens de Aanbestedingsfase, betrof de zoektocht naar een ontwerp, in combinatie met een onderhoudsbeleid, dat kosteneffectief zou zijn, gegeven de boetes die golden voor een te lage infraprestatie. Een serie van ‘optimalisatie workshops’ werd georganiseerd, waarin de ontwerpteams voor de spoorconstructie, energievoorziening en beveiliging en beheersing werden gevraagd hun schattingen over hoeveelheden onderhoud en storing expliciet te maken. Op deze wijze konden schattingen van levensduurkosten gemaakt worden en (idealiter) de effectiviteit van ontwerpmogelijkheden beoordeeld worden. Dit laatste bleek, echter, slechts beperkt haalbaar. Eén van de grootste obstakels bleek de bereidwilligheid van de ontwerpteams om aan dit proces mee te werken; deze nam pas sterk toe aan het einde van het proces.

De derde studie, die binnen ProRail (Railinfrabeheer) bekend stond als LCM+ (Life Cycle Management Plus), betrof de ontwikkeling van een eerste set nationale richtlijnen voor het plannen van spoor- en wisselvernieuwingen. Het management had hierom gevraagd, omdat praktische, transparante beleidsregels afwezig bleken en omdat er een plek werd voorzien in bovenbouwvernieuwing (BBV). Het was een expliciet onderdeel van de doelstelling om zo’n beleid te baseren op life-cycle kostenberekeningen. Een proces werd uitgedacht en uitgevoerd, dat bestond uit vier fasen (binnen ca. 9 maanden). De eerste fase bestond uit het genereren van een set van kansrijke maatregelen voor het op korte termijn reduceren van het BBV volume. Vervolgens werden deze maatregelen in regionale ‘pilotprojecten’ verder geanalyseerd in relatie tot concrete, geplande spoorvernieuwingen. De derde fase bestond uit het generaliseren van de bevindingen in deze pilots, c.q. het afleiden van beleidsregels. De laatste fase betrof tenslotte het opstellen van een meerjarenprognose voor BBV. Het project resulteerde in een set beleidsregels, die algemeen als kosteneffectief en robuust werden beschouwd, resulterend in een (voorzichtige) besparing van zo’n 10% in BBV.
en levensduurkosten. Er werden tevens aanbevelingen gedaan voor een revisie van het productieplanningsproces om te garanderen dat LCM+ maximale aandacht zou krijgen. Eind 2001 startte de implementatie van LCM+, begeleid door het kernteam (inclusief de auteur). Hoewel verwachte besparingen naar verwachting grotendeels gerealiseerd zijn, bleken er obstakels in de regio’s te zijn om LCM+ veel aandacht te geven. De toets van de productieplannen werd bemoeilijkt, omdat de Regio’s geen tijd bleken te hebben, de voorgestelde wijziging in het planningsproces niet werd doorgevoerd en uniforme technische criteria (voor het voordragen van projecten voor vernieuwing, zgn. afkeurcriteria) afwezig bleken.

**Conclusies over de effectiviteit van de LCC-gebaseerde aanpak**

Omdat de casus ‘real-life’ processen betroffen, die aanzienlijk verschillen in context, opzet en uitvoering (deels door omstandigheden, deels door een ‘leercurve’ bij de auteur), konden ze niet geëvalueerd worden als laboratoriumexperimenten. Niettemin konden conclusies getrokken worden, dankzij de verzameling van gegevens via identiek opgezette ex-post interviews (op basis van vooraf gedefinieerde criteria) en officiële documenten uit de casus. Besluitvormers in de drie casus herkenden en waardeerden het vermogen van de ontwikkelde aanpak om de besluitvorming te voeden met nieuwe, kwantitatieve data. Dit resulteerde onder bepaalde voorwaarden in:

- validatie of falsificatie van ideeën over effecten van ontwerp en onderhoud;
- beoordeling van de levensduurkosten van een brede set ontwerp-/onderhoudsopties;
- verbeterde communicatie en onderling begrip onder de participanten;
- de acceptatie van nieuwe, life-cycle gebaseerde strategieën.

De rol en invloed van de beslissingsondersteuning varieerde echter sterk over de drie casus en alleen in de laatste casus werden alle bovengenoemde functies duidelijk gerealiseerd volgens de deelnemers. Tijdens de implementatie bleek een deel van het draagvlak toch door omstandigheden (weer) weg te zakken. Maatgevende factoren voor het aanwezig of afwezig zijn van succes, die vanuit de interviews naar voren kwamen, zijn de aanwezigheid van ‘commitment’ van het top management, het soort beslissing (bijvoorbeeld of conditie-afhankelijk onderhoudsbeleid mogelijk is), de beschikbaarheid van onderhoudsgegevens en de wijze waarop de ondersteuning geboden is. De conclusie is dat de besluitvorming beïnvloed kan en via LCC, maar dat het vinden van draagvlak in de huidige praktijk behoorlijk moeilijk is. Verder leidt de (initiële) toepassing van LCC volgens de deelnemers niet tot een verkorting van de besluitvorming. Een reden hiervoor is de afwezigheid van een gemakkelijk beschikbare set gegevens en een erkende ‘kennisbank’ over lange-termijn effecten van ontwerp en onderhoud. De verzameling van gegevens is het moeilijkst voor nieuwe technologieën (zoals bij de HSL-Zuid), maar ook op het conventionele net (bij ProRail) bleek dit lastig. Het is te verwachten dat LCC kan bijdragen aan het continu verbeteren van deze situatie, omdat het aannames vastlegt, die op termijn valideerbaar en verbeterbaar zijn.

Een aantal principes voor procesontwerp lijken een deel van het succes van de derde casus te verklaren, zoals het instellen van een breed panel van experts binnen de organisatie en het toewijzen van pilots, *e.g.*, het door kleinere teams laten uitwerken van ontwerp- en onderhoudsvarianten. Een belangrijk uitgangspunt is ook dat de analist expertise binnen (en
buiten) de organisatie kan raadplegen en een voor iedereen toegankelijke set van invoerdata en aannames samenstellen. Tijdsdruk veroorzaakt door te strakke procedures (zoals bij de HSL-Zuid) kan zorgen voor foutieve invoer en een chaotische besluitvorming: validatie en acceptatie kosten tijd. Dit betekent ook dat realistische verwachtingen over LCC moeten worden verstrekt aan besluitvormers: LCC kan al de moeite waard zijn om impasses in de besluitvorming te doorbreken, maar belangrijke, duurzame effecten kunnen alleen verwacht worden in een omgeving, waar het leren over systeembrede effecten van individueel handelen onderdeel is van het dagelijkse werk. Een aantal aanbevelingen is hiervoor gedaan.

Aanbevelingen voor verder onderzoek en voor de infrabeheerder

Ten eerste zijn een aantal aanbevelingen gedaan voor verder wetenschappelijk onderzoek. Het wordt aanbevolen om de hier uitgewerkte LCC aanpak toe te passen in omgevingen waar nog weinig ‘harde data’ beschikbaar zijn via bijvoorbeeld interne informatiesystemen, internaald benchmark-onderzoek of technisch onderzoek. In dat geval moet de aandacht eerst liggen op het ontwikkelen van een betrouwbare proces van informatieverzameling en – gebruik en het verkrijgen van draagvlak, in plaats van op het ontwikkelen van geavanceerde modellen. Verder wetenschappelijk onderzoek kan zich richten op het opzetten van een modular beslissingsondersteunend systeem voor het ramen van levensduurkosten van spoorwegen. Zo’n systeem zou geregeld uitgebreid kunnen worden, wanneer verbeterde input beschikbaar komt (bijvoorbeeld modellen voor degradatiertrends en voor het bepalen van kosten van niet-beschikbaarheid). Verder dient er aandacht besteed te worden aan de wijze waarop inschattingen van experts “gekalibreerd” kunnen worden aan de hand van empirische gegevens.

Ten tweede zijn specifieke onderwerpen in het ontwerp en onderhoud van railsystemen aanbevolen voor ondersteuning door LCC. Het wordt daarbij aangeraden om LCC selectief toe te passen in zorgvuldig uitgekozen, breed opgezette studies. Dit zou de voorkeur moeten hebben boven het gebruik van LCC als element van projectaanvragen (zoals nu het geval bij ProRail), omdat er anders een risico op strategisch gebruik is, c.q. LCC als middel om projecten geaccepteerd te krijgen. Een minimale vereiste is dat deskundigen worden betrokken, die niet verantwoordelijk zijn voor de onderzochte (voorbeeld-)projecten. Behalve voor de bovenbouw kan dergelijk onderzoek wellicht ook nuttig zijn voor analyse van beslissingen binnen de disciplines ‘energievoorziening’ en ‘treinbeveiliging en -beheersing’ en beslissingen, die meerdere disciplines omvatten. Infrabeheerders zoals ProRail zouden vanuit het LCC concept kunnen proberen om een topdown visie op de toewijzing van budgetten aan de verschillende disciplines en onderhoudsregio’s op te zetten. Het criterium is dan het te verwachten rendement (kosteneffectiviteit) in termen van punctualiteitsverbetering en duurzaamheid van het railnetwerk. Op dit moment worden budgetten vooral toegewezen op basis van jaarlijkse budgetaanvragen, die ‘bottom-up’ vanuit de disciplines en regio’s komen, terwijl de tweede casus voor de HSL-Zuid liet zien dat een meer analytische aanpak waarschijnlijk mogelijk is. Ook kan LCC van dienst zijn om de effecten van de verdeling van ‘slots’ (tijd) tussen onderhoud en exploitatie te analyseren en om de mogelijke effecten van infragebruiksheffingen in kaart te brengen.

Ten derde is voorgesteld om werk te maken van het opzetten van een normatief ‘procesmodel’ voor life-cycle georiënteerde ontwerp-, exploitatie- en instandhoudings-
processen. Dit kan eerst vanuit een theoretische insteek opgezet worden, op basis van de onderhoudsliteratuur. Hierin kan bepaald worden welke computersystemen benodigd zijn, welke actoren welke gegevens dienen te verzamelen en wanneer de life-cycle effecten (infrastructuur en kosten van eigendom) van algemeen beleid en concrete beslissingen onderzocht dienen te worden. Aandacht dient ook besteed te worden aan de onzekerheden in het schatten van life-cycle effecten.

Ten vierde zijn suggesties geformuleerd voor het verbeteren van condities in de organisatie van ProRail voor een life-cycle benadering van het ontwerp en onderhoud. Het onderbrengen van kwaliteitscontrole en -verbetering, in eerste instantie voor het bovenbouwonderhoud, in een centraal team zou hierin een belangrijke rol kunnen spelen. Het team moet duidelijke bevoegdheden hebben, zoals het opstellen van centrale maatstaven voor het plannen en selecteren van maatregelen van groot onderhoud en vernieuwing en die statistieken opstelt rondom levensduren, infrastructuur en -defecten en onderhoudskosten per locatie. Deze kunnen gebruikt worden voor trendanalyses. Deze afdeling dient ook van tijd tot tijd experts van buiten de organisatie te benaderen. Op deze wijze zou het ook mogelijk moeten worden een deel van de budgetten al eerder toe te kennen aan de regio’s, zodat zij de tijd hebben om hun plannen optimaal te richten op de locaties waar het geld het hardste nodig is. In feite zouden de Europese infrabeheerders (veel meer) samen dergelijke analyses moeten uitvoeren om ervaringen uit te wisselen en om samen benodigd technisch onderzoek te organiseren.

Tenslotte zijn suggesties gedaan met betrekking tot de institutionele omgeving. Het wordt aan het Ministerie van Verkeer & Waterstaat aangeraden om meer uitleg te vragen aan de infrabeheerder, bijvoorbeeld omtrent gerealiseerde levensduren, en om alternatieven te zoeken voor budgettoewijzing op kasbasis. Het ministerie dient ook te bestuderen hoe zij een life-cycle gebaseerde instandhouding van het Nederlandse net kan stimuleren in de financiering van het ontwerp- en onderhoudsproces; de ‘a fond perdu’ financiering van de bovenbouw moet in eerste instantie worden aangepakt. Het ministerie kan er verder voor kiezen om prestatieverbetering van de railsector actief te ondersteunen door het sponsoren van onderzoek en het faciliteren van besluitvorming, indien obstakels overwonnen moeten worden. Een voorbeeld van een dergelijk obstakel is het installeren van nieuw ‘equipment’, dat duurder is in aanschaf dan het bestaande ‘infra-bestand’, maar dat betere prestaties zal leveren (in termen van veiligheid, beschikbaarheid, betrouwbaarheid en levensduurkosten).

Hoewel financiële arrangementen per land verschillen, is de nationale overheid doorgaans de belangrijkste (directe of indirecte) financier van het spoorsysteem. Het wordt daarom verwacht dat de bovenstaande aanbeveling ook van belang kan zijn voor andere nationale overheden in Europa (gezien de bevindingen uit hoofdstuk 2).
A man is flying a hot air balloon and realises he is lost. He reduces height and spots a man down below. He lowers the balloon further and shouts, "Excuse me. Can you help me? I promised a friend I would meet him half an hour ago, but I do not know where I am."

The man below says, "Yes, you are in a hot air balloon, hovering approx. 30 feet above this field. You are between 40 and 42 degrees north latitude and between 58 and 60 degrees west longitude."

"You must be an engineer", says the balloonist.

"Yes, I am", replies the man. "How did you know?"

"Well”, says the balloonist, "everything you have told me is technically correct, but I have no idea what to make of your information, and fact is I am still lost."

The man below says, "You must be a manager."

"Yes, I am", replies the balloonist, "but how did you know?"

"Well", says the man below, "you did not know where you are, or where you are going. You have made a promise which you have no idea how to keep, and you expect me to solve your problem. The fact is, you are in exactly the same position you were in before we met, BUT NOW IT IS SOMEHOW MY FAULT."

*An Internet joke.*

*N.B. in my view, the clue is that both should try and do better.*
About the author

Arjen Zoeteman was born in Gouda on September 30, 1976. After graduating from the Christelijker Lyceum, he studied Systems Engineering, Policy Analysis and Management (SEPAM) at Delft University of Technology (DUT). His majors were in transport policy and logistics. For his Master’s project, he carried out research at the Directorate General of Infrastructure of the Regional Government of Madrid and at the Innovation Department of the Dutch railway contractor Strukton Railinfra. During this project, he started to investigate the possibilities of life-cycle cost analysis to support decision-making in the railway sector.

Having graduated in 1998 cum laude and as the ‘best student’ of his year, he joined the Section of Transport Policy and Logistics’ Organisation (Faculty of Technology, Policy and Management). His PhD research focused on ways to stimulate ‘life-cycle thinking’ in the European rail sector. The research was done in collaboration with the Section of Road and Railway Engineering (Faculty of Civil Engineering and Geosciences). The research was embedded in the Netherlands Research School for Transport Infrastructure and Logistics (TRAIL) and sponsored by ProRail, Strukton Railinfra and the European Rail Research Institute. The author was involved in several large projects concerning the Dutch high-speed line and Prorail’s track renewal policy.

In addition to the PhD work, the author has given several lectures at DUT, supervised a few Master’s projects and coached project groups at the post-academic Rail Systems Engineering course of Delft Toptech since 1999. He has also been a board member of the Traffic and Transport Engineering Department at the Dutch Royal Institute of Engineers (KIVI-NIRIA) since 1999 (Treasurer since 2000) and has organised several KIVI meetings on railway management. In 2003, he joined the Road and Railway Engineering Section as a researcher. Information about current projects can be found at: http://go.to/ArjenZoeteman.
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