A LIFE CYCLE APPROACH IN RAILWAY DESIGN AND MAINTENANCE: OPPORTUNITIES AND OBSTACLES

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Abstract
Infrastructure managers increasingly have to deliver to defined performance levels (e.g. RAMS and life cycle costs). Because rail infrastructure consists of expensive components which have long life spans, it is important to review the cost and performance impacts of decisions during the remaining life span of the components. Such a systematic analysis of long-term, system-wide impacts should make it possible to justify investments in particular, "optimal" designs and maintenance regimes. In practice, tools, data and knowledge required for estimating long-term maintenance impacts are still relatively absent in the European rail sector. This paper describes an approach, which provides quantitative support in the review of design and maintenance strategies in settings where empirical maintenance data are not readily available. A decision support system named *LifeCycleCostPlan* is used for the purpose. The impacts of the approach are discussed, using one example case study and the results from ex-post evaluation interviews with stakeholders from three case studies. Success was realised, but, on the other hand, organisational barriers were found, which can hinder the implementation of more life-cycle-based design and maintenance strategies.

Keywords: Life cycle cost plan
Topic Area: A1 Road and Railway Technology Development

1. Introduction

The setting, in which construction and preservation of railway networks is performed, changes rapidly. Since the 1980s, initiatives have been taken in many countries to introduce market forces in railway systems; after North America and Japan in the 1980s, the European Union followed in the 1990s. The European reform model consists of the creation of separate, independent infrastructure managers (IMs); this should have a number of advantages. [EU, 1996]. Firstly, it should create transparency in cost accounting and decentralise public interference. Secondly, it should allow competition; new operators can enter the European railway market under non-discriminatory regimes. Thirdly, it allows governments to develop a 'level playing field' between rail and other transport modes, using differentiated regimes for investments or user charging between rail, road and air; these regimes can include internalisation of external costs (e.g. costs of traffic accidents and environmental pollution). An important driver for the European reform was a new belief in the potential role of railways in combating traffic congestion, accidents and environmental pollution.

Although reforms in many EU member states are still ongoing, an important consequence has already come to light. The new IMs, i.e., the former infrastructure departments of the state-owned railways of the 20th century, are appointed with an entirely new responsibility. They are increasingly being asked to deliver specified performance levels in terms of infrastructure availability and reliability (to the operators), while they have to negotiate heavily on necessary input factors such as government funding. As Fig.1 shows, they are key players in a sector where business-oriented performance contracts will become more and more common.

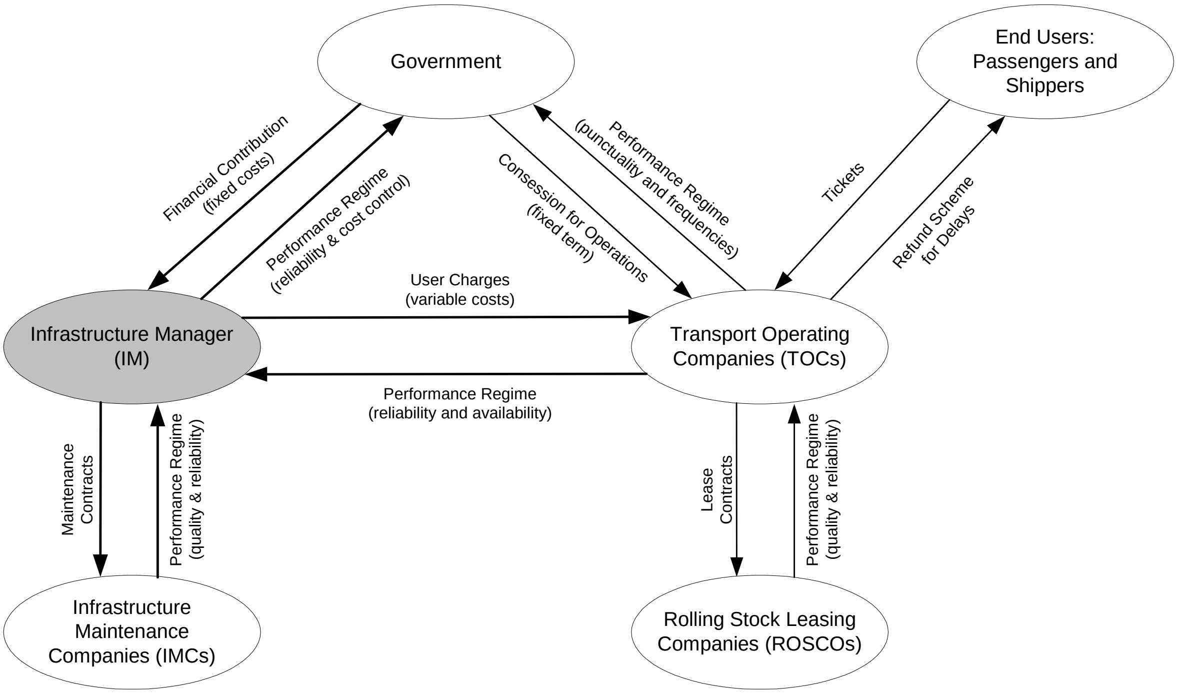

Figure 1. Possible contractual landscape in a strongly restructured rail sector

Adapting to this rapidly changing environment means a drastic change for the design and maintenance staff, who worked in the integrated railways in a rather autonomous manner, viz. on the basis of craftsmanship and “implicit decision making”; the infrastructure department was organised in a hierarchical manner, with technically skilled chiefs in the central headquarters making the final decisions in their discipline [Swier and Vollenhoven, 1998]. It seems that the change towards more transparent design and maintenance practices still largely has to be made; this was emphasized by the problems of the British *Railtrack* (now *Network Rail*), but is also seen on other networks. For instance, many IMs state to have backlogs in track renewal, but they have difficulty in demonstrating the precise effect of these renewals in terms of deteriorated infrastructure performance [Jovanovic and Zoeteman, 2002].

There seem to be a number of problems to overcome in this change. Firstly, despite much research, not all infrastructure deterioration processes are already well enough understood to “translate” them into quantitative relationships between investment and maintenance decisions and infrastructural quality effects; this might result in longer-term effects being underestimated [Ferreira, 1997; Veit, 2003]. Secondly, the long-term, capital-intensive nature of rail infrastructure conflicts with the preference of many governments and shareholders for short payback periods on investments and quick performance improvements. Rail infrastructure is a very capital-intensive production asset to construct and maintain; in the EU, costs of infrastructure cause 30% to 45% of the total operating costs [Vandenbroeke, 1994; Profillidis, 2001]; because of the long life spans of the components, decisions have a high degree of irreversibility, and consequences of bad decisions (e.g. low construction qualities or insufficient preventive maintenance) have to be dealt with for a long time. Thirdly, although the IM should be the actor which is capable to incorporate such effects in decision making, either implicitly or explicitly, there are many incentives in the organisational structure not to do so. 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 small changes, year by year. This is not a peculiarity of railways; for instance, Vonk and Smit [1996] found in a representative survey that practically no maintenance department in the Netherlands applies 'zero-base budgeting', but "re-uses" usual maintenance budget figures which are incrementally changed on the basis of, for instance, the financial position of the company.

This paper investigates the possibilities to assist designers and maintainers, within the new IMs, to increase the quality and transparency of design and maintenance decisions in the face of these new requirements. It elaborates a decision-support approach which is based on the technique of Life Cycle Costing (LCC) and which already functions in a setting where empirical, "measured" data on maintenance processes is hardly available. Section 2 introduces the approach, in which a decision support system (DSS) forms the centrepiece; the DSS structure is presented in Section 3. Section 4 briefly discusses an application in a case study on the Dutch railway sector. Section 5 summarises a number of findings, which were obtained from evaluation interviews with the participants of this case study and from two other case studies. Finally, Section 6 ends with a number of conclusions and recommendations.

2. Decision support for life-cycle-based strategies

In 1997, a start was made at Delft University of Technology to develop an approach which can assist designers in maintainers, in a pragmatic manner, in showing consequences of different design and maintenance strategies. It was decided to base the approach on LCC, a technique from the field of engineering economics, which provides approved logic to balance costs and revenues on the short and long term. 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, 1991]. With LCC, different design and maintenance solutions can be tested on their total costs of ownership and operation, including the additional costs and revenues lost due to failures or planned maintenance (possessions); the decision solutions to be considered should all meet the minimal functionality requirements, e.g., design speeds, axle-loads and curve radii. LCC would thus allow a systematic and objective choice between different solutions.

A requirement for LCC is the availability of estimation models which relate input variables (e.g. quality of materials, labour costs, interest rates) with output variables such as costs of construction, maintenance and non-availability. Considering the state of the art in maintenance management in the railways, it was expected that few usable, detailed data sets would be available for such models; degradation data, maintenance histories, and cost levels are (still) hardly collected in relation to individual assets (e.g. different railway track sections and switches), which is necessary input for empirical degradation models. As a consequence, it would be necessary to use input from maintenance experts in the railways and to seriously test the sensitivity of outcomes to the assumptions made by those experts. It was therefore chosen to develop a decision support system, which would include such estimation models and which could process expert judgements. The DSS was expected to assist in the following decision-making processes:

- evaluating different physical designs or maintenance strategies quantitatively;

- analysing impacts of restrictive operational and financial conditions for maintenance;
- developing maintenance plans, aimed at optimising system life cycle costs;
- training staff in recognising system-wide impacts of design and maintenance decisions.

The developed DSS, *LifeCycleCostPlan*, will be described in the next section, but first we will reflect on the way to use this DSS. Since it would be mostly based on expert judgements, the facilitation of an adequate data collection and validation process was considered to be of crucial importance. A procedure was developed, in which reliability of the data is taken care of in two ways. First, chauffeured sessions are organised, in which the participation of experts from, at least, different organisational units is a prerequisite. In the sessions, a process of data validation takes place: depending on the progress, the input data itself is discussed or the DSS is used for 'face validation' of the assumptions. Each of the participants has to elaborate feasible alternatives and make his judgments on the input parameters *prior* to the session and has to show references to underpin his judgments. During the sessions these assumptions are discussed and the participants get the opportunity to adjust their judgment or to come up with new information. In most cases, one judgement results after discussion; however, a range of input data can be tested as well. Secondly, means were included in the DSS to test the sensitivity of the outcomes to certain inputs. Rankings of the alternatives are summarised in a single table for a range of scenarios, which provide the decision makers an insight into the robustness of decision alternatives and the impact of the "guestimates" from experts.

3. The LifeCycleCostPlan DSS

A DSS usually consists of a database, a model-base, and a user interface [Bidgoli, 1989]; in our DSS, this distinction was not that clear as all elements were implemented in a Microsoft Excel environment. Moreover, the user interface was less sophisticated, as this author served as the 'DSS chauffeur' who would tune the DSS, in order to match the specific information needs of the group of experts and decision makers.

A number of calculation steps were distinguished to obtain the final outputs i.e. the expected life cycle costs, reliability and availability levels within the defined time horizon; the steps start with the expected transport load on the railway line, which is step by step translated into required maintenance and renewal (M&R), costs and traffic disruption, and, finally, life cycle costs. This is done for each design and maintenance alternative to be analysed. Fig. 2 shows the calculation processes and input data tables (on the left and right side of the figure). The dotted arrows indicate the use of data from a data table for the calculation, while the other arrows indicate the sequence in the calculation. The estimation steps are discussed below.

Calculation Process 1: Estimating the loads on the infrastructure

Quality degradation is usually a function of either time (in years) or load on the track (in cumulative gross tons or number of train passages); using a reference timetable, a gross tonnage is therefore first calculated according to UIC Leaflet 7.14, which provides a formula how to include impacts of different speeds, axle-loads and wheel diameters in the tonnage carried. Many factors may influence component degradation rates (loss of quality per unit of time or load); reliance on expert knowledge is inevitable, when the maintenance data administration is poor. As an example, a head-hardened rail type typically has a lower wear rate than a standard rail type: if wear is the dominant factor for the rail life, such as in curves or in heavy axle-load environments, this rail will carry more traffic, i.e., gross tons.

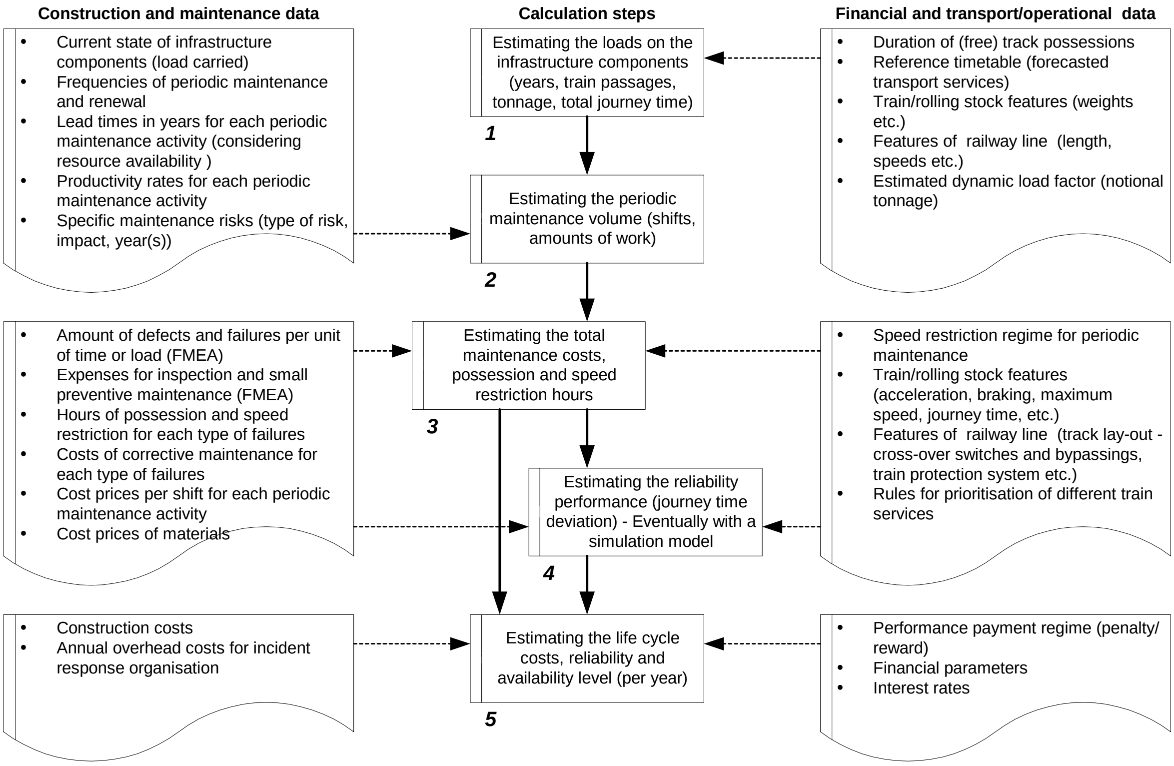

Figure 2. Structure of the LifeCycleCostPlan DSS

The reference timetable, needed for calculating traffic load on the track, can be specified for different spans of time, in order to express traffic growth or decline. It contains the expected number of trains and train-sets for the different services (specified to e.g. axle-loads and train weights) as well as the number of operational hours per day (per direction). Apart from tonnage calculation, this timetable can also be used for extracting the scheduled journey time, being the sum of the journey times of all trains on the particular track section during a particular period of time. This factor can be used, later on, as a basis for measuring the percentage of traffic that is delayed. Finally, the timetable reveals available non-operative hours, i.e., slots for maintenance possessions which do not disrupt operations.

Calculation Process 2: Estimating the periodic maintenance volume

Amounts of periodic M&R, i.e. M&R works with intervals of more than a year, are derived from the forecasted load. Time spans between M&R activities can differ for different components, due to the presence of different materials, years of installation and traffic loads. These thresholds can be defined directly in a tonnage limit (cumulative tons) or indirectly via an infrastructure quality indicator; as already mentioned, decline of the quality indicator has, again, a relation with cumulative time or load. In this way, the intervals for major overhaul or renewal, are derived for each component. Thresholds for major M&R can be interdependent: renewals can be harmonized in time and place (clustering renewals on adjacent track sections) and components (combining renewals of different infrastructure components). In addition, it is well possible that a particular M&R activity harms the condition of another component: for instance, the ballast bed can degrade as a result of frequent track tamping.

On the basis of estimated M&R intervals, the required number of work shifts can be calculated for each of the activities. Once M&R is initiated for a particular component and infrastructure segment, it can be realised in a single year or in a couple of years. The required amount of work shifts in a single year is calculated on the basis of production speed, the duration of set-up and finishing tasks, the available duration of track possessions and the number of years, defined by the user to complete the particular activity. Fig. 3 shows, as an illustration, a plot of the output of the second step (with fictive data).

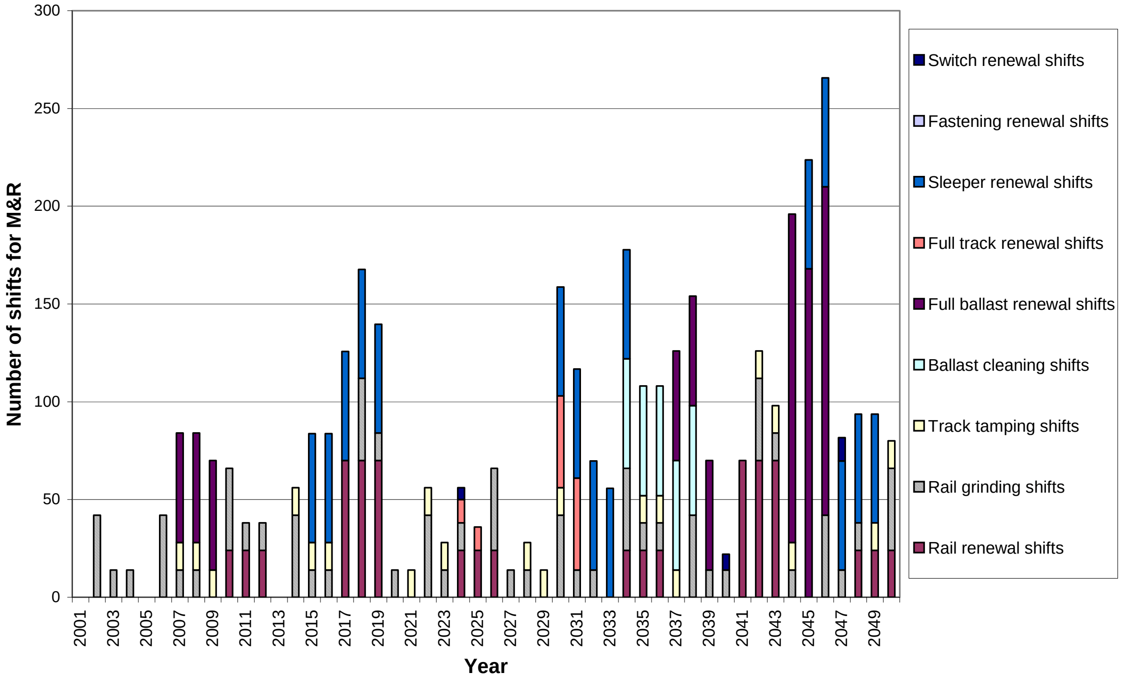

Figure 3. Example of intermediate output LCCP (after step 2)

Calculation Process 3: Estimating maintenance costs and possession hours

Based on the number of work shifts per year, the total costs for periodic maintenance can be calculated from the unit costs per kilometre (materials) and costs per work shift (labour and machines). A number of days with speed restrictions, possibly with different, gradually increasing speed limits, are included as well. Hence, total hours of possession and speed restriction can be calculated directly from the number of work shifts.

Moreover, impacts of small maintenance and failures are added in this step: amounts of small maintenance and failure time are partly related to the cumulative tonnage or years in service of the infrastructure components and partly independent from loads (e.g. inspection intervals). Costs, possessions and speed restriction hours involved in the inspection, small maintenance and failure repair are included in the model *per ton carried* or *per year*. Small maintenance and failure repair consists of a variety of tasks and failure types, which is why summarised estimates are used; Failure Mode Effects Analysis is a technique which be used to produce these estimates.

Calculation Process 4: Estimating infrastructure performance impacts

The first three steps have delivered estimates on the maintenance costs, as well as the planned and unplanned track possessions and speed restrictions, for each of the analysed decision alternatives; the result of this step will be that speed restrictions and possession hours are converted into figures, which fit the applicable Performance Regime. Valuing the impaired availability and reliability is an inevitable step: a possession or speed restriction on a regional, low-density line will have less severe consequences in terms of higher operating costs and lost revenue than on an international high-speed line.

Insight into the impacts of the infrastructure performance on operating costs and revenues is essential for the assessment of the life cycle costs; *LifeCycleCostPlan* can take care of the valuation of possessions and speed restrictions. A model has been included, which estimates the cumulative train delay minutes and cancellations, based on the acceleration and braking performance of the trains and a number of assumptions. Main assumptions are that a speed restriction does not result in train cancellations and knock-on impacts on later scheduled trains, whereas unplanned track blockage leads to a cancellation of all scheduled trains during those hours. Validity of the assumptions under the specific conditions should be verified. With the use of the reference timetable the average amount of affected trains can be estimated. This disruption leads to a rise in operating costs and a loss in revenues; average figures on the impact of a train delay minute and a train cancellation have to be available. The total amount of train delay minutes is also influenced by the availability of passing tracks or rerouting options, and the braking and acceleration performance of the trains. However, in more complex situations, simulation tools can deliver the required input on train delay times.

Calculation Process 5: Estimating the infrastructure life cycle costs

Finally, the total running infrastructure costs during the analyzed period, needed for construction, maintenance, renewal and performance penalties, can be estimated. With the defined performance regime, which is to the impacts on the transport operating process, the estimated performance of the infrastructure is converted into actual penalties. The costs of the delay are related to the transport value, defined by the traffic types and intensities. In case that the decision concerns the construction or upgrading of infrastructure, initial investments can be included as well; design alternatives vary in their designed quality, cost and future maintenance needs. Construction costs can be put into *LifeCycleCostPlan* as a lump-sum cash flow during the first couple of years or in a more detailed specification, if this assists in the comparison of alternatives.

Once all cash flows are available, the financing costs can be derived, using the real interest rate. First, all future costs are discounted to their *present value*, which is their value in the Base Year i.e. the year in which the decision is made. Next, based on the total present value of the life cycle costs, the annuity is calculated for each of the alternatives. This is the so-called *annual (flat) performance fee*, which has to be paid every year to cover interest, depreciation, and running costs. Also the possibility is included to label particular, unlikely, maintenance activities as ‘specific risks’, which are depicted separately as risk margins on top of the annuities. Section 4 provides a brief overview of an application of the LCC approach on the Dutch network in the years 2000 and 2001.

4. An example of application: Dutch track renewal policy

M&R expenditures on the Dutch rail infrastructure are significant, about 400 million Euros in the year 2002; the track system alone consumes about 70% of this amount. Not only are the expenditures high, they also vary in time due to the age distribution on the network, the realisation of projects in previous years, and the quality of performed maintenance. Timely insight into required renewals is crucial in order to level out renewal peaks over the years. Life cycle cost analysis of different M&R strategies can therefore be a useful method to identify optimal prioritisations between proposed renewal projects on the rail network [Zoeteman and Van Zelm, 2001]. An important trigger for *ProRail*, the Dutch rail network manager, to start the so-called LCM+ (Life Cycle Management Plus) project was a strong increase in the track renewal volume, forecasted for the period 2000-2010. It was hoped that policy rules could be developed, which would lead to important reductions in the renewal volume, without harming the quality and availability of the infrastructure on the long run. A prerequisite for new policy rules to be accredited was that the cost-effectiveness had to be demonstrated explicitly for a wide range of (future) conditions, which is why it was decided to support the process with the *LifeCycleCostPlan* DSS and to involve track experts and planning analysts from each of the four Maintenance Regions of ProRail.

The project was performed during 2000 and 2001 and consisted of four phases. In the first project phase a top-30 of promising measures was composed. In the second project phase the regional teams assisted in the life cycle cost analysis by performing a number of pilots. Ten pilots were selected in order to represent the diversity of track and switch types as well as the different operational features (main track, side-track and yards). Most pilots were tracks or switches, preliminary scheduled for renewal in 2002; the regional teams were requested to develop feasible maintenance and renewal strategies. A data collection checklist, which describes required input data and data formats, was used for the collection of input data by engineering staff, which were free to collect empirical data (e.g. laboratory tests, computer simulation, supplier information, maintenance history and actual maintenance cost rates) or make expert judgements. *LifeCycleCostPlan* was first used during a number of Chauffeured Sessions in order to show the outcomes from the regional pilots and to perform validity tests. The central staff, the (other) regions as well as external experts, critically reviewed the solutions and assumptions of each regional pilot. In the third phase central staff performed an extensive sensitivity and scenario analysis for each of the pilots, which provided a firmer base for deriving generic policy rules. The phase was finished with a policy session, in which the results of the analyses were discussed, and the agreement on sixteen rules being acceptable to all Maintenance Regions and applicable to a wide range of situations on the network. In the fourth phase, the financial impact of the new rules was quantified in a new forecast for the years 2003-2020.

The drafted process is illustrated for one of the pilots, the *Baarn-Amersfoort Pilot*. The tracks between the cities of Baarn and Amersfoort are part of the main rail network, and are quite intensively used (UIC class 3, with especially a lot of passenger traffic). On these tracks so-called Nefit-track was installed; the tracks are named after the Dutch fastening system used. Nefit was used on a large scale in the 1970s when the Dutch network needed a rapid upgrading to accommodate higher axle-loads, since it could be installed quickly. The disadvantage showed to be that the quality deterioration of the fasteners is hard to monitor, which causes a realistic risk of gauge widening in the current state of the tracks. ProRail and the Ministry of Transport have decided to renew a huge amount of about 890 kilometers of Nefit-track during the years 2000-2007. According to ruling practice the tracks are completely renewed with a renewal train and possibly some materials in good shape will be sold as scrap to railway contractors; re-using the materials has been abandoned anyway since the closure of the Regeneration Depot of the Dutch Railways after the restructuring. In this pilot, a proactive approach was adopted: at the nearby yard of Amersfoort a sleeper renewal for more than 6 kilometres of track was planned. A quality check confirmed that both sleepers and rails from the main track could be re-used, although there were problems to be overcome. There would be enough Nefit-sleepers available in good order, but they were designed for the UIC54 rail profile, whereas, at the yard, NP46 rails, the former Dutch rail standard, were in use.

The outcomes for the distinguished M&R alternatives under normal operating conditions are shown in Fig. 4 and include the costs of main-line track possessions. Each of the alternatives is composed of a Z-variant, which is the renewal option for the yard, and an H-variant, the renewal option for the main line. Applicability of the Z-variants also depends on the chosen renewal variant on the main track (H-variant). A number of options for re-use in the yard renewal were envisioned (Z-variants):

1. the Nefit-sleepers could be renovated with new fastening plates for NP46;
2. the NP46 rails could be attached to the Nefit-sleepers with the use of so-called ‘chocolates’ (cast iron strips to fill the gaps);
3. both UIC54 rails and Nefit-sleepers could be re-used.

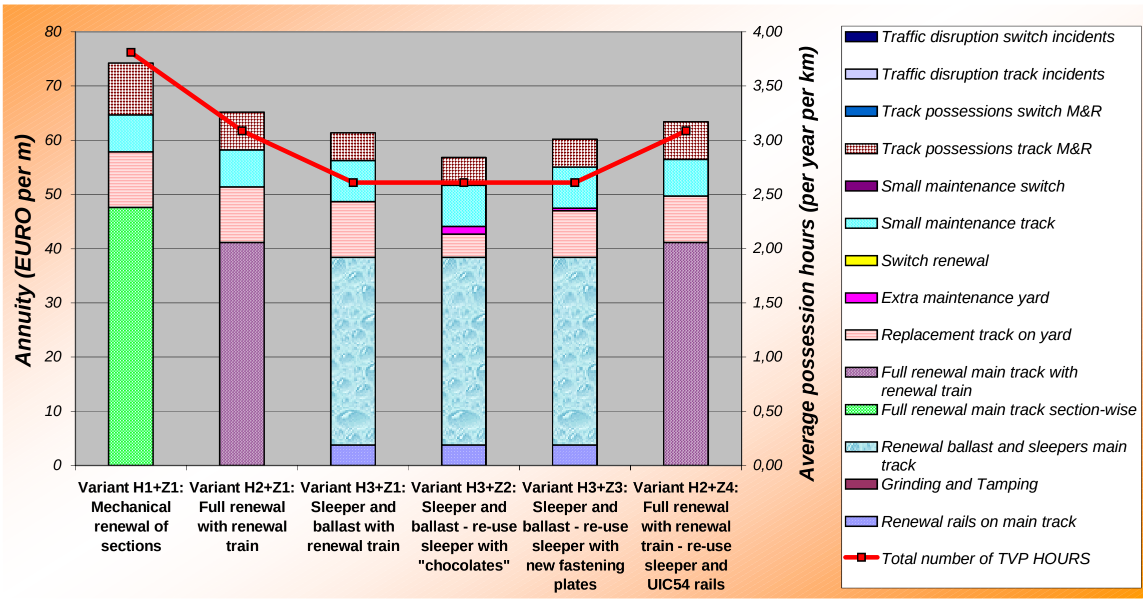

Figure 4. Indicative outcomes for the Baarn-Amersfoort pilot, inc. railway yard renewal
(Variant Z1 is the installation of new sleepers on the yard of Amersfoort)

A partial renewal of the main track in combination with the “chocolates solution” was expected to lead to a life cycle cost reduction of at least 13%, and an immediate reduction of the required investment. The chocolates solution was in first instance being debated, but a field test on an operational line showed the safety and durability of the solution for branch lines with annually some corrective maintenance. A promising result of this pilot proved to be that the stability of the ranking of the different alternatives.

It was decided to use the heavily debated “chocolates solution” and the project was executed in 2003, according to the expectations. Apart from that, the pilot delivered data, which could be used to distil more general policy rules on the re-use of main-line components on side-tracks. Although instant re-use of components requires more project planning and co-ordination, all Regions agreed that the inexpensive renewal of branch lines is worth the effort.

LCM+ was finished in 2001 with a new track renewal forecast for the years 2003-2020, which showed an average reduction of the required budget by 10%, i.e., about 20 million Euros per year, based on cautious assumptions on the applicability of the rules and including costs of extra, life-extending maintenance. Implementation of the rules, which were accredited by the management, in the M&R planning cycle has been taken care of in 2002. Nevertheless, refinement and monitoring of the policy rules will remain important to keep the findings from LCM up to date.

5. Findings on the decision-support process

LCM+ was one of three case studies performed between 1998 and 2002 in the field of railway design and preservation, in which the *LifeCycleCostPlan* DSS was used to support decision makers. It had been preceded by two other case studies, performed during the tender of the new Dutch high speed line, HSL South, in which bidders for the railway system construction were asked to include a period of 25 years of maintenance in their bids. They would also have to pre-finance the entire construction cost and would only be paid back the entire cost (through quarterly fees) if their performance, i.e., system reliability, is about 99%. It can be imagined that this was also a challenging environment to test the LCC approach, not only due to the heavy requirements but also due to much time pressure [Zoeteman, 2001]. The provided support in all three case studies was evaluated with the participants in the decision-making processes, after each study had been completed; the participants were asked to score how the LCC support had influenced the decision making in their view. A standard set of indicators on the quality of decision making was used, based on an evaluation framework proposed by Thissen and Twaalfhoven [2000]. The findings from these evaluations are extensively discussed in Zoeteman [2004]; here we will have to limit the discussion to a number of key findings. First of all, with the case studies, it could be demonstrated that the LCC support can assist decision makers in the following functions:

1. *Identifying decisive cost drivers and performance killers.* First of all, it proved to be able to develop an insight into the factors determining costs and performance of the rail infrastructure system. A quantitative analysis of life cycle costs helps to select important cost drivers, including those factors causing high operational costs ("performance killers"). This function can already be performed with relatively imprecise data.

2. *Improving the quality of data/information used for decision making.* With the availability of the model a "quantification" of the discussion is possible; instead of arguments, such as "this design is well maintainable" or "this strategy will deliver high availability levels", more precise arguments can be developed. Hidden, "tacit" knowledge of designers and maintainers becomes available for review; moreover, through a process of review, the use of empirical M&R data is stimulated.

3. *Training staff in identifying system-wide impacts of decisions.* Once a rough model of the problem situation is available, possible impacts of different decision options can be modelled. By "playing" with the input data, staff can be helped in identifying system-wide impacts; according to the interviewees, the graphical output of the DSS, and the cost breakdown charts in particular, proved to be helpful for that. Further, the quantification of the discussion can help invalidate possible prejudices; an example is that types of maintenance, mentioned as major drawbacks of a particular decision alternative, show to have only a small influence on the total costs or performance on the long run, and vice versa (Pareto-analysis).

4. *Stimulating creative competition and exchange of ideas among design and M&R teams.* Under conditions, the quantification of the problem situation can trigger the search for a wide range of feasible decision alternatives. Sufficient peer pressure and an open ambiance seem to be necessary conditions for this search; computer-supported brainstorm sessions showed to work positively.

5. *Assessing the effectiveness of design modifications and M&R solutions.* Under conditions, it proves to be possible to assess the applicability and effectiveness of design and M&R strategies in a reliable, trustworthy way. Although absolute outcomes will deviate in reality from the estimated ones, the interviewees from the LCM+ project generally believed that a fair relative ranking of decision alternatives was demonstrated for defined operational scenarios. In the case of innovative technologies, large uncertainty margins might, however, complicate this picture.

6. *Improving relationships and communication between participants.* Under conditions, it proves to be possible to improve the communication between the participants and their overall relationships. The LCM+ project changed their attitudes, according to the participants themselves; for instance, the group took some M&R approaches seriously, which were beforehand seen as someone's "personal hobby".

7. *Building (durable) commitment to the preferred design or M&R strategies.* Under conditions, the LCC-based approach can create commitment to desirable changes in the design and management of rail infrastructure. For instance, in the LCM+ project, it was possible to adopt a set of new policy rules, which avoid short-term thinking in the planning of M&R works.

The case studies have shown that there are significant opportunities for supporting decision makers through the technique of Life Cycle Costing; the desirability and usability of quantitative information on life cycle costs was obvious for the interviewees. It was found that LCC can be much more effective in terms of creating commitment to desirable changes in existing design and maintenance practices, when it is embedded in an analysis process in which relevant experts and decision makers participate. Participants can become "ambassadors" to propagate the gained insights. Clear evidence could be obtained that the design of the analysis setting is as important as the quality of the LCC study itself.

However, the finding that the design of the process is rather important implies that there are also significant obstacles to implementing LCC. They are discussed below, including possible solutions and precautions which were found to be helpful in our case studies:

1. *Perceived/ actual integrity of the study.* It seems that political factors can make or break a large part of the success of the project. Political pressure can create a sense of urgency among the stakeholders, which can work out positively in performing the study; as an example, the expected, large increase in track renewal work created a sense of urgency to commence the described LCM+ project. However, if the LCC study touches upon topics, where stakeholders have strongly varying views, interests or preferences, there is a risk that the quality of the study and the input data in particular are affected. Since LCC crosses many boundaries in the rail system, this is a realistic risk, perhaps especially in restructured railways where actors have emerged who take only responsibility for parts of the system. A few precautions should always be taken in the process design and control, particularly in order to guarantee the trustworthiness of the analysis and the LCC analyst(s). The core team has, firstly, to list all data and assumptions used, and to refer to the used information sources. Secondly, a transparent list of assumptions enables external content experts to be approached for reviews; this might not be feasible in every situation (e.g. tender processes), but should at least be promoted. Nevertheless, we have to conclude that process design and control, involving the various stakeholders, is not necessarily sufficient in "political situations". LCC studies without transparent assumption lists should be a criterion *for the decision makers* not to rely on the study.

2. *Position of the study.* The study should best be organised as a "stand-alone process", which produces a piece of advice for the daily decision-making processes. This provides status to the process and enables participants to consider daily practice from a distance. Support from sponsors in the central management is an essential factor to stress a sense of urgency and to guarantee that participants allocate sufficient working time to the project. In temporary project organisations, the analysis should preferably be part of the organisational chart. If actors do not consider the project as their ownership, the chance that their attitude is changed in the desired direction as a result of the analysis is small. Although it might not be manageable to involve all, an actor analysis has to be made to identify key stakeholders. These actors should be involved in one way or another. The level of participation can vary; for instance they can be involved in the definition of the objective and work approach (e.g. list of starting points), invited for special feedback sessions or for workshops, where solutions are developed and intermediate results of assessed solutions are discussed.

3. *Organisation of an authoritative expert panel.* A crucial factor is that those persons can be involved in an expert panel, which are generally acknowledged within the

organisation or within the rail sector as a whole as “content experts”. In the case of assessing new railway designs, also M&R experts need to be part of the team in addition to the engineering staff. Since they work in a different part of the organisation, and do usually not co-operate in daily work, involving them requires some organisational boundaries to be crossed. Preferably, the experts involved represent the stake-holding parties, so that they can propagate the results as “ambassadors” and avoid “black box feelings” to rise among these parties. In the case of assessing M&R policies, it should be included in the project objectives that the expert panel can continue to function afterwards in, more or less, the same composition for monitoring the implementation and the actuality of the developed M&R strategies.

4. *Process of developing and assessing alternatives.* Decision alternatives do not arise automatically; the participants need an open, creative ambiance to seriously consider alternatives which depart from their usual approaches to design and M&R. The approach taken by the core team makes a difference. The LCM+ project showed that commencing the project with a computer-supported brainstorm session helped in generating alternatives and creating this ambiance. Further, it works out very well to assign the elaboration of different design or maintenance alternatives to different, small expert teams. The LCM+ pilots proved to help in developing technically feasible, pragmatic alternatives; the feedback and review of the pilots in plenary meetings of the entire expert panel created a kind of “creative competition”.

5. *Assessment of the alternatives through the DSS.* It seems that the DSS should preferably function as a “background tool” in the process. If the role of the DSS is stressed too much, participants can lose the feeling that they have an influence on the process, which puts both their commitment at risk and reduces their participation in the review and validation of input and output data. Nevertheless, the DSS automatically needs to play a more central role in the design phase of a new railway for assessing different future scenarios, when many uncertainties have to be dealt with. A proper way is then to involve experts already in the design of the DSS modules.

6. *Type of decision arena: uncertainties, data and “optimisation limits”.* There are also “natural limits” to the capability of LCC as a tool for changing railway design and M&R policies. For instance, track M&R seems an eminent area for developing life cycle cost, condition-based strategies. Long life spans and heavy investments are involved, while at the same time the track condition can be monitored well and time is available to develop alternative M&R alternatives. Detailed insight in the applicability of LCC in other areas has not been obtained in this study, but it might be well possible that in other technical areas, such as the signalling and power supply system, other issues are at stake. Maintenance may not be well possible through condition-based maintenance strategies and, instead of technical necessity, there may be other drivers for renewal of components. An example is the introduction of new electronic systems and software in order to avoid the system becoming obsolete [Dowling]. Another limit is the availability of empirical data, which determines to a large part the uncertainty levels in the outcomes; if the uncertainties are large, it is probably more difficult to select clear “winners” among the different decision alternatives. Availability of empirical data depends on the data and knowledge available at the problem owner and the experiences with particular decision alternatives. Clearly, as maintenance is more and more recognised as an explicit area for management, the quality of the collected maintenance data will become of a higher level; as an example, at the moment, maintenance data are still mostly collected for accountancy purposes and not for the purposes of composing ‘maintenance histories’ of individual assets.

7. *Implementation in daily decision making.* Not much data could be collected on this factor yet, but a co-ordinated implementation seems to be crucial in the case of new M&R strategies. It seems that the largest risk for implementation is caused by the priorities of actors, who have not been involved actively, since they did not go through the same "process of awareness" as the participants of the LCC study.

Looking backwards at the case studies, it has to be noted that only in the LCM+ project, described in Section 4, the LCC support clearly led to a new set of more cost-effective renewal strategies being adopted. In the preceding case studies, the LCC studies had to be performed in a hectic environment (an international consortium) under much time pressure. Many conflicting views and many uncertainties, with respect to the future operating conditions on the Dutch high speed line, complicated the progress in these studies.

It seems that it is hard to drastically change the conditions, under which decision support has to be provided; although the set up of a participative policy analysis has a positive impact on the commitment of actors to the outcomes, LCC support itself is surely not a panacea for creating a more systematic, transparent decision-making process. Even for relatively simple LCC studies, there should be strong commitment from top managers, in order to mobilise the required expertise; improving this situation is no doubt an important challenge in today's railway environment. In addition, LCC will usually take much effort and time, in order to guarantee a trustworthy analysis process and commitment from participants; this is clearly a drawback in the case that decisions have to be taken more quickly.[1]

6. Conclusions and recommendations

This paper demonstrated an approach to support designers and maintainers of railway infrastructure in analysing the long-term effects of their decisions, using the technique of Life Cycle Costing (LCC). A decision support system for the estimation of life cycle costs was presented, and its application in real-life case studies was discussed. LCC proved to have the ability to improve the quality and transparency of railway design and maintenance decisions, in terms of more life-cycle-based design and maintenance strategies. LCC can provide a framework for sound discussion; tacit knowledge, available in the "heads" of designers and maintainers becomes available for systematic review. It allows the development of transparent planning rules for maintenance and renewal (M&R), which can be optimised with respect to costs of ownership and traffic disruption.

Creating the commitment of different stakeholders was found to be of great importance, because LCC studies require data which "cross" organisational boundaries (e.g. construction budgets, maintenance budgets, technical subsystems, outsourced work loads) and because LCC studies can result in strategies which influence the different parts of the railway system (e.g. more investment in construction can reduce levels of maintenance). Suggestions were made in the text to improve the process of participation of those stakeholders in the study, but it was recognised that the organisation should also be "ready" for this kind of analysis. Top managers should make clear to the design and maintenance staff that the application of life-cycle-based strategies has to be demonstrated for decisions taken; without their support, the quality of the LCC study can be affected (through lacking co-operation) and implementation of new strategies will be difficult.

Continued leadership seems necessary to safeguard the implementation of life-cycle-based strategies in the railway environment. It is therefore suggested that LCC can better serve as a part of a broader 'management change programme', aimed to create a more

[1] For instance, the LCM+ project required a year of preparation (i.e. getting different parties committed to the project) and a year of analysis (i.e. performing the pilots and developing generic policy rules).

systematic, transparent process of decision making, than as an incidental, ad-hoc study, in which only engineers at lower echelons in the organisation take an interest.

Much work seems to be necessary to introduce life-cycle-based approaches in railway design and maintenance, and it is suggested that the European rail infrastructure managers initiate serious efforts to systemise data processing on asset degradation and M&R, which are not only useful for the purpose of accountancy, but also for the purpose of maintenance management. Database systems should be adopted which can deal with the segmented character of rail infrastructure assets, in order to collect the data in relation to the individual assets (e.g. typical maintenance costs, failure levels, and component degradation patterns per type of switch). The benefits for taxpayers (reduced costs of ownership of railway networks) and travellers (reduced disruptions to travellers, caused by infrastructure maintenance and failures) should justify these efforts.

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