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Life Cycle Costing applied to railway design and maintenance: creating a dashboard for infrastructure performance planning

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Abstract

The restructuring of the railways in the European Union and the increasing number of 'Build, Operate and Transfer' contracts necessitate performance-based infrastructure management. Since 1998 Delft University of Technology provides a decision support system (DSS) for analysing the long-term impacts of design and maintenance decisions in relation to future maintenance and traffic conditions. A computer tool combines is used to estimate total life cycle costs. Infrastructure availability and reliability forecasts are included in these estimates. In this paper DSS design is described and the effectiveness of the decision support in a real-life case study is briefly demonstrated. The DSS proved to be valuable, as it enabled testing the cost-effectiveness of decision alternatives.

1 Introduction

In the last decade the maintenance of railway infrastructure in Europe has become a different profession than what it was in more than one hundred years before, due to a rapidly changing environment. In the first place EU directive 91/440 requires that a separate entity has to provide the railway infrastructure in order to stimulate profit-driven (Trans-European) transport operations and transparent cost accounting *[1]*. In most EU Member States the restructuring of the railway is in progress. Secondly, the operational conditions on many railway lines are increasingly stringent in order to facilitate more diverse transport services (e.g. light rail), more trains per hour, longer operating hours and an improved punctuality. These conditions conflict with the efficient scheduling of maintenance works and lead in the long run to an increase in maintenance as well.

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In the third place government regulations imply more and more restrictions, related to railway safety, labour safety and noise levels, while government grants for maintenance are not easily acquired anymore.

Besides the increasing performance requirements set by government and operators, the Infrastructure Manager (IM) is often confronted with worn-out assets, backlogs in maintenance and track possessions claims for construction and upgrading projects. In order to deal with the heavy short-term cost and performance demands and to guarantee the RAMS (Reliability, Availability, Safety and Maintainability) of the rail network on the long term, professional 'asset maintenance management' is needed. This is an even more crucial issue due to the growing number of 'Build Operate Transfer'–like contracts, of which the Dutch High Speed Line Zuid is an example *[2]*.

This means that maintenance plans cannot be based only on individual experiences of line supervisors any longer, but have to be composed and optimised to realise explicitly performance targets for the rail system as a whole. A *systematic, transparent* approach to identify maintenance needs, plan maintenance and renewals, and schedule the works within the timetable is needed. The following steps in developing asset management can be distinguished:

- **Asset Registration**: the first step in maintenance management is to establish a complete asset register that is able to link data of inspections, maintenance history and operations (e.g. tonnage) with specific assets;
- **Maintenance Concepts**: as for planning and forecasting, the (average) maintenance and inspection needs per type of asset should be known, e.g. Mean Time To Restore Services and Mean Time Between Failures. The introduction of new component types and maintenance technologies, such as Condition Monitoring, can influence these parameters. Maintenance concepts are developed through Failure Mode Effects Analysis (FMEA); they contain the prescribed frequencies of inspections and maintenance *[3]*;
- **Life Cycle Cost Optimisation**: to realise an optimal trade-off between maintenance and renewal (M&R) life cycle cost analysis (LCCA) should be applied. LCCA can be applied on the level of individual projects or for developing a comprehensive maintenance strategy, also to be reflected in the *maintenance concepts*. A decision support system can facilitate the estimation of the life cycle costs under different conditions in order to test the robustness of the solutions *[4]*;
- **Optimisation of Work Planning and Scheduling**: in a following step it is possible to prioritise and cluster M&R works in the medium or long term and to optimally co-ordinate the planned works with the availability of resources, such as track possessions, labour and machines. An expert system like ECOTRACK, which can plan track renewals based on predefined rules and quality criteria, assists the planning of major (track) maintenance and renewal projects *[5]*, while small maintenance tasks can be clustered in regular, e.g. monthly, cycles;
- **Performance Based Maintenance Contracts**: finally the IM could choose to outsource the well-defined ongoing maintenance tasks to contractors and to develop maintenance contracts which are based on explicit performance indicators, e.g. track quality and incident response times.

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Most European Infrastructure Managers make efforts to develop and implement the information systems, planning tools and work procedures required for professional infrastructure management, as described above. However, implementing the mentioned "building blocks" is a long-winded process and still in an early phase, even the step of Asset Registration is in many railways still in a problematic early stage *[6]*. Due to the increasing pressures it is however essential to increase the quality and transparency of design and maintenance decisions already in absence of the above-mentioned planning tools and structures. In this paper the concept and actual use of a decision support system (DSS) is discussed, which can assist decision makers quickly in identifying long-term costs of ownership and operation (life cycle costs), caused by specific design and maintenance choices. In section 2 the DSS and the procedure to use the DSS within decision-making processes is discussed. Section 3 provides a description of a case study in order to demonstrate the applicability of the approach. Section 4 contains a discussion and a number of conclusions.

2 Design of a life cycle costing tool

'Approved logic' to balance costs and revenues on the short and long term can be found in the Life Cycle Costing (LCC) concept. 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 *[7]*. It can however also function for maintenance or renewal strategies, although they are in some way "end-of-the-pipeline solutions": possible savings to be expected are smaller than during the design stage.

Life cycle costs are the result of a complicated set of (partly) uncertain conditions. An analysis of the sensitivity of the life-cycle costs to a wide range of operational conditions is required to enable decision-makers in selecting a decision alternative with the best guarantee to be cost-effective and robust. The concept of a decision support system (DSS) can eminently contribute in this respect. A DSS can be defined as a computer-based data processing system developed and used to improve the effectiveness and efficiency of decision makers in performing semi-structured tasks, partly having a 'judgmental' character *[8]*. It usually consists of a database, a model-base, and a user-interface. Models from the model-base can be used in a flexible way in order to respond to management information requests. A DSS with the capability to estimate infrastructure life-cycle costs should be able to assist in several tasks:

- evaluating different physical designs or maintenance strategies quantitatively;
- analyzing the impacts of (restrictive) operational and financial conditions for infrastructure maintenance;
- supporting the development of maintenance plans that aim at optimizing the life cycle costs of the system;
- training engineers and managers in recognizing system-wide impacts of design and maintenance decisions.

Such a DSS proved not to be available off-the-shelf in 1997, although there were some developments in other railways as well. With these goals of application in mind, Delft University of Technology and partners from the European rail industry decided to develop such a DSS named *LifeCycleCostPlan* (LCCP). As responsiveness of the DSS was considered of more importance than direct interactiveness, 'chauffeured system use' was deemed satisfactory and inevitable: a skilled 'DSS chauffeur' functions as an intermediary between the computer model and the decision maker. Only a few other railways in Europe and North America have developed such types of DSSs. Examples are the TRACS system of the North-American railways and the DSS of TU Graz and Austrian Federal Railways *[9, 10]*. Often contents of the tools have been developed for a specific goal, and applications are still limited or have been considered as confidential and proprietary to the railway company.

The final outputs of LCCP are the estimated life cycle costs, reliability and availability, delivered by each of the analyzed design and maintenance alternatives during the predefined time period. Below the calculation processes are described. For each calculation process a model is used that consists of a set of equations.

Calculation Process 1: Estimating the loads on the infrastructure

Quality degradation is a function of time (in years) and load on the track (in cumulative gross tons or number of train passages). A gross notional tonnage can be calculated according to UIC leaflet 7.14. The formula takes the impact of different speeds, axle-loads and wheel diameters into account. A lot of factors influence the degradation *rate* (loss of quality per unit of time or load), which is reflected in a tonnage- or calendar-based threshold for maintenance. As an example, a hard-headed rail type has a lower wear rate than a standard rail type. If wear is the determining factor, mostly in curves or in heavy axle-load environments, the hard-headed rail can carry more tons due to a lower wear rate. For the calculation of the gross tonnage a so-called 'Reference Timetable' is used. The timetable can be specified for different time intervals in order to express traffic growth or decline and 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). Beside the tonnage, this timetable can also be used for calculating the (annual) scheduled journey time. This is the sum of the journey times for all trains on the particular track section. Some 'Performance Regimes' use this for the calculation of the reliability level. The Timetable also reveals the available time for non-disrupting possessions.

Calculation Process 2: Estimating the periodic maintenance volume

Based on the forecasted load on the infrastructure, the amount of periodic M&R can be estimated. These major M&R works have intervals of more than a year. Maintenance thresholds or limits have to be specified for each major infrastructure component, as well as the loads already carried. The input can differ for different parts of the analyzed infrastructure segment, due to the presence of different materials, years of installation and traffic loads. These thresholds can be defined directly in a tonnage limit or indirectly via an infrastructure quality indicator.

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Thus the residual life spans, and the intervals for major overhaul or renewal, are derived for each component (for the distinguished homogenous parts of the analyzed infrastructure segment). Thresholds for major M&R can be interdependent: renewals can be harmonized in time and place (clustering of renewals on adjacent track sections) and components (clustering renewal of different infrastructure components). Based on the 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 realized in a single year or in a couple of years. The user can define the number of years, in which a type of M&R activity has to be finished. Finally, the required amount of work shifts in a single year is calculated. Input data are the productivity rates for each activity, specified in a production speed and duration of set-up and finishing tasks, and the available duration of possessions.

Calculation Process 3: Estimating maintenance costs and possession hours

Based on the number of work shifts per year, the costs per kilometer (materials) and the costs per work shift (labor and machines), the total costs for periodic maintenance can be calculated. A number of days with speed restrictions can be set as well. The total hours of possession and speed restriction can thus be calculated directly from the number of work shifts. Moreover, in this step the impacts of small maintenance and failures are added: 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.

In the DSS the costs, possession and speed restriction hours involved in the inspection, small maintenance and failure repair *per ton carried* or *per year* can be defined. Small maintenance and failure repair consists of a variety of tasks and failure types, which is why summarized estimates are used. The impact on the life cycle costs is small, compared to the investments in new construction and periodic M&R. The Failure Mode Effects Analysis (FMEA) technique, can be used to produce estimates on the amount of small maintenance and failures.

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 analyzed decision alternatives. A valuation of the impaired availability and reliability is however an inevitable next 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.

LCCP can take care of the valuation of possessions and speed restrictions. 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, to be reflected in cost rates for train delay minutes and train cancellations. The total amount of train delay is also influenced by the availability of passing tracks or rerouting options, and the trains' acceleration performance. The costs of the delay are related to the transport value, and thus the traffic types.

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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. The main assumptions are that a speed restriction does not result in train cancellations and knock-on impacts on later scheduled trains and that an unplanned track blockage leads to a cancellation of the trains scheduled during those hours. Validity of the assumptions under the specific conditions should be verified using more advanced dynamic simulation models.

Calculation Process 5: Estimating the infrastructure life cycle costs

Based on the earlier calculation steps, the total running infrastructure costs during the analyzed period can be calculated, needed for maintenance, renewal and performance penalties. Based on the Performance Regime the estimated performance of the infrastructure is converted into actual penalties, and eventually rewards, which reflect the impacts on the transport operating process. In case that the decision concerns the construction or upgrading of infrastructure, initial investments have to be included as well. Design alternatives vary in their designed quality and maintainability (e.g. M&R thresholds). Together with the maintenance strategy the initial quality determines future maintenance needs. On the other hand this quality is also reflected in a "price tag". Construction costs can be put into LCCP 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 decision alternatives.

Once the cash flows for initial investments and running costs are available, the financing costs can be calculated based on the (real) interest rate. First, all future costs are discounted to their *present value*, which is their value in the Base Year that the choice for one of the decision alternatives is being 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 events as 'specific risks', which are depicted separately on top of the annuity bar.

The main feature of LCCP, in contrast to for instance *ECOTRACK*, is that it does in principle not contain, and not need, track quality degradation models. LCCP is therefore not designed as an expert system with predicting capabilities, but as a "sophisticated calculator" for the key relations between transport loads, maintenance thresholds and life cycle costs. Such models, in which a high level of uncertainty is involved, can however be integrated into LCCP, or used separately to deliver some of the input data. This has been a principal design choice, which transfers the responsibility for estimating maintenance frequencies almost entirely to the engineering and maintenance staff. The strength of LCCP is that the assumptions of the maintenance staff become available for a detailed validation and analysis. The crux in the analysis becomes thus the facilitation of an adequate data collection and validation process. A Data Collection Checklist, which describes required input data and data formats, is used for the collection of input data by engineering staff. Many data sources can be used; the procedure to guarantee reliability of the outcomes, using face validity tests (amongst others), is described in *[11]*.

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3 Application of the approach in a case study

Total Maintenance and Renewal expenditures on the Dutch rail network have been both about 200 million Euros in the year 2002. The Tracks Subsystem consumes about 60% of maintenance and 80% of renewal expenses. Not only are the expenditures very high, they also vary in time due to the age distribution on the network and the realization of projects in previous years. A timely insight into the costs and track possessions is crucial in order to level out the renewal volume over the years. Insight into the life cycle costs of different renewal strategies is in this respect a method to realize an optimal prioritization between proposed renewal projects on the railway network. In 1999 a prognosis showed a strong increase in the renewal volume required between 2000 and 2010. This was an important trigger for the Dutch IM, *Railinfrabeheer*, to start the LCM+ project.

Objective of LCM+ was to develop policy rules for tracks and switches that lead to an important reduction and leveling out of the renewal volume without reducing the quality of the network. 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. Besides staff from Headquarters, four sub-teams of technical track specialists and planning analysts from each of the four Maintenance Regions were participating to develop and assess cost-reducing strategies. 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.

In total 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 preliminary scheduled for renewal in 2002; the regional teams were requested to develop feasible maintenance and renewal strategies. A special management module was developed for LCCP, where overall data on operating conditions could be stored (e.g. interest rates, M&R production speeds and unit costs) and which could steer the estimation processes of the pilots.

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, reviewed critically the solutions and assumptions of each regional pilot. In the third phase central staff assisted in an extensive sensitivity and scenario analysis, performed for each pilot. This also contributed to deriving policy rules, applicable to a wide range of situations on the network. The phase was finished with a Policy Session, in which the results of the analyses were discussed with the experts, and the agreement on sixteen rules being acceptable to all Maintenance Regions. In the fourth phase the financial impact of the new rules was quantified in an adapted Renewals Prognosis for the years 2003-2020. The drafted process will be illustrated for one of the pilots, the Baarn-Amersfoort Pilot, in detail.

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The tracks between the cities of Baarn and Amersfoort are part of the main rail network, and are quite intensively used (UIC class 3[1]), with especially a lot of passenger traffic). On these tracks so-called 'Nefit-track' has been used, which has been used on a large scale in the 1970s when the Dutch network needed a rapid upgrading to accommodate higher axle-loads (22.5 tons). Its advantage was a rather inexpensive and quick installation. However, the disadvantage showed to be that the quality deterioration of the fasteners is hard to monitor, and considering the current state of the tracks the risk of gauge widening due to broken fastening clips has become a realistic risk. *Railinfrabeheer* 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 the standard policy the tracks are completely renewed with a renewal train, and possibly some materials can be sold as scrap to railway contractors. Since the railway restructuring the stock depot of Dutch Railways, where used materials were stored and renovated, has been closed. In this pilot however a proactive approach was chosen: at the nearby yard of Amersfoort a sleeper renewal for more than 6 kilometers 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. Enough Nefit-sleepers in good shape could be obtained, but they were designed for the UIC54 rail profile, whereas at the yard UIC45 rails are in use. A number of options for re-use in the yard renewal were envisioned, further referred to as Z-variants:

1. the Nefit-sleepers could be renovated with new fastening plates for UIC45;
2. the UIC45 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.

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 some small corrective maintenance once per year. The applicability of the Z-variants is also depending on the chosen renewal variant on the main track (H-variant). The outcomes for the pilot under normal operating conditions are shown in figure 4. In these outcomes also the costs of track possessions for main line and yard have been included.

A partial renewal of the main track in combination with the "chocolates solution" is expected to lead to a life cycle cost reduction of at least 13%, and an immediate reduction of the required investment. A remarkable and promising result of this pilot proved to be that the ranking of the different alternatives (combinations of H- and Z-variants) proved to rather stable to changing operating conditions and changes in the assumptions. A joint tender of the works on main track and yard has started in 2002; execution of the works takes place in 2003.

[1] UIC class 6 lines are the least used railway lines, which comprises lines on yards and side-tracks.

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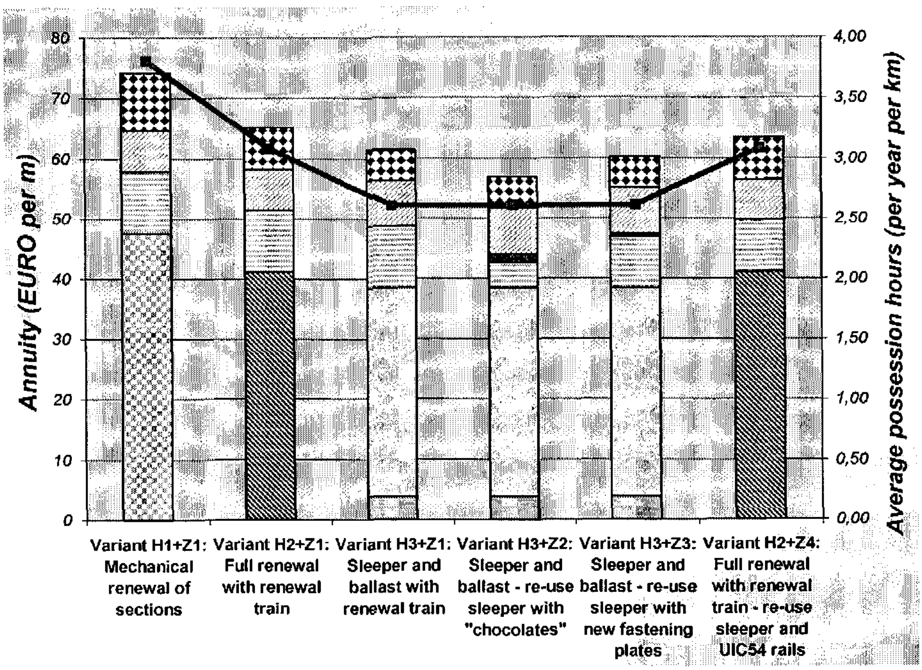

Figure 1: Indicative outcomes for Baarn-Amersfoort pilot including yard. The different sections of the columns represent the cost breakdown to different maintenance activities – more information can be found in [6]

Considering the large renewal quantities, many sleepers in good shape will be available for a great number of yards and branch lines. Although instant re-use of components requires more project planning and co-ordination, all Regions agreed that it was worth the efforts. A number of planning rules on partial renewal and instant-re use of Nefit-sleepers were therefore formulated, also confirmed by the outcomes of other pilots. Compared to the usual policy (solution H2+Z1) the 'smart rules' prove to reduce both short-term expenses and life cycle costs.

4 Discussion and conclusions

The applicability of a Life Cycle Costing (LCC) approach was demonstrated in the LCM+ project of the Dutch rail infrastructure manager, *Railinfrabeheer*, which was finished in 2001; an annual reduction of the maintenance and renewal budget of 10% or about 20 million Euros proved to be feasible *[11]*. The Management has accredited the new rules and implementation is now taken care of, as a more timely co-ordination between the different departments of *Railinfrabeheer* has to be facilitated. The acceptance of the LCM+ rules shows that LCC is not by definition in conflict with budgeting practices in the railway organization, which is often thought. On the contrary, it can function as a tool to help decision makers in prioritising projects systematically.

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LCM+ was one of the case studies performed between 1998 and 2002 in the field of railway design and maintenance, in which the approach and the use of the *LifeCycleCostPlan* DSS proved to provide a framework for sound discussion. A detailed evaluation will become available in 2003 in a PhD thesis of Delft University of Technology. The approach proves to have impacts both in terms of *contents* (chosen designs and maintenance strategies) and *interaction between actors* (quality of communication). It helps the participants in becoming sensitive for influential mechanisms in the performance of railway infrastructure, and, in this respect, the DSS can be seen as a dashboard for the Infrastructure Manager (IM) for planning the desired infrastructure performance for a desired cost of ownership. Besides, the increased awareness of 'cost-drivers' and 'performance killers' in the infrastructure management process can support negotiations on risk allocation and performance regimes with other actors. Further development of the DSS could focus on methods to manage and improve the *process of participation* and the '*responsiveness'* of the DSS to information needs. 'Probability analysis' techniques (e.g. Monte Carlo simulation), benchmarking with other railways and the consultation of external experts could improve the quality of analyses further.

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