Life cycle cost analysis for managing rail infrastructure

Concept of a decision support system for railway design and maintenance

Arjen Zoeteman
Faculty of Technology, Policy and Management
Delft University of Technology
Delft
The Netherlands

EJTIR, **1**, no. 4 (2001), pp. 391 - 413

Received: March 2001
Accepted: November 2001

In the last decade managing railway infrastructure in Europe has changed compared to the century preceding it. Due to the restructuring of railways, which has resulted in separate Infrastructure Management and increasing performance demands from governments and Transport Operating Companies, infrastructure performance has become an important issue. Reliability requirements, budget limits, and operational conditions, such as the time available for maintenance, are becoming increasingly strict.
As a response Infrastructure Managers (IMs) have started to develop computer-based tools for a quantitative analysis of the (long-term) impacts of design and maintenance decisions. These tools should enable IMs to systematically optimise and underpin their budget needs, minimise the total costs for a required performance level, and guarantee the infrastructure quality in the long run. Although progress has been made over the last years, these tools are still in an early phase of development, and have not yet been successfully implemented in the design and maintenance management processes.
In this paper an approach based on Life Cycle Costing has been developed, which is able to support decision-making on design and maintenance quantitatively, even in absence of sophisticated maintenance planning tools, using expert judgement beside empirical data. Key to the approach is a decision support system (DSS) for analysing the long-term impacts of design and maintenance decisions on reliability, availability and cost of ownership.
The DSS combines data from different management areas, such as construction, maintenance, financing and transport operations, in order to make estimates of the life cycle costs. Infrastructure availability and reliability are included in the analysis of life cycle costs, as they have an impact on the costs and revenues of transport operations.
The DSS concept and its application during the tender for the Dutch High-Speed Line are presented. Both results and obstacles are discussed. Especially in a design phase a lot of uncertainty is involved in the analysis. The DSS proves to be a valuable tool for testing the

robustness of design and maintenance decisions and for focusing the discussion on the important cost-driving factors.

1. Introduction

Due to a rapidly changing environment, managing railway infrastructure in Europe has changed in the last decade compared to the century preceding it. In the first place EU directive 91/440 requires that, in time, a separate entity has to provide the railway infrastructure in order to stimulate profit-driven (trans-European) transport operations and transparent cost accounting of infrastructure and operations [European Commission DG VII, 1997]. In most EU Member States as well as other European countries the restructuring of the railway is in progress, the split-up and privatisation of British Rail being the most radical example [Root *et al.*, 1997]. In the second place the operational conditions on many railway lines are increasingly strict in order to facilitate more diverse transport services (e.g. light rail and high-speed trains), more trains per hour, longer operating hours and an improved punctuality. These conditions conflict with the efficient scheduling and execution of maintenance works and can, in the long run, lead to an increase in maintenance and renewal as well. In the third place government regulations imply more and more restrictions, related to railway safety, labour safety and noise levels, whereas government grants for maintenance are no longer easy to acquire [see e.g. Hazelaar *et al.*, 1997]. Beside the increasing performance requirements set by government and operators, Infrastructure Managers (IMs) are often confronted with worn-out assets, backlogs in maintenance and track possession claims for construction and upgrading (e.g. for increasing the track capacity and the installation of new technology).

In order to deal with the short-term cost and performance demands *and* to guarantee the RAMS (Reliability, Availability, Safety and Maintainability) in the long run, systematic 'maintenance management' of the railway assets is needed [Wilson, 1999]. Maintenance used to be highly based on individual, subjective experience from local track supervisors and was considered "something that just needed to be done" [Swier, 1998]. However, the changing environment gives rise to many questions, which need to be answered in a structured, well-reasoned way, such as:

- What are the availability and reliability expectations of infrastructure designs?
- Which risk margins have to be applied in construction and maintenance cost estimates?
- What is the impact of increased traffic intensities and loads on maintenance?
- What are the penalties allocated to the Infrastructure Manager in case of availability-reducing incidents? What is the optimal duration of track possessions considering traffic disruption and work efficiency?
- Which amount of preventive maintenance yields a minimal cost of ownership and operation?

The railway system proves to be quite a complicated system. First, operations and infrastructure influence each other in various ways. The quality of the trains (rolling stock) influences the wear of the infrastructure and thus the amount of maintenance and renewal needed. Secondly, infrastructure failures, but also planned possessions for maintenance, influence the reliability of the operations. An important aspect of rail infrastructure is that the assets (or *infrastructure components*) have long life spans and once installed it is very costly and complicated to modify the initial design. Decisions in design and maintenance will thus have a long-lasting impact. If for instance preventive maintenance is reduced systematically, the assets can become worn-out quickly and this can result in disproportionately high maintenance costs [Jovanovic and Zoeteman, 2001].

Therefore, IMs need maintenance analysis and planning tools that enable them to systematically analyse and optimise budget needs, minimise the total costs for the required RAMS level, and guarantee the quality of the railway assets in the long run.

The following ingredients for maintenance management can be distinguished:

- *Asset registration.* The first step in maintenance management is to establish a complete asset register that is able to link infrastructure quality measurements, maintenance work history and transport data (tonnage) with the asset location and the specific asset.
- *Maintenance concepts.* As for planning maintenance frequencies, the degradation and failure patterns and repair methods should be known (Mean Times To Restore Services and Mean Time Between Failures) in order to plan inspection and maintenance tasks. Maintenance concepts are developed through Failure Mode Effects Analysis [Moubray, 1997].
- *Life cycle cost analysis.* To realise an optimal trade-off between investment and maintenance, life cycle cost analysis (LCCA) should be applied. Maintenance concepts, additional expert judgements and empirical data are the information sources. A decision support system should facilitate the estimation of the life cycle costs under different operational conditions in order to test the robustness of the chosen solution [Zoeteman, 1999a].
- *Computer-assisted work planning.* A planning system should assist the prioritisation and clustering of maintenance and renewal (M&R) works in the medium term, and the planning of materials and resources, such as track possessions, personnel and machines [Zaalberg, 1998].

Most European Infrastructure Managers are making efforts to develop and implement the tools required for professional maintenance management, as described above. However, in particular the steps related to life cycle cost optimisation and computer-assisted work planning are in an early phase of development. In some countries, such as Austria, France, Germany and The Netherlands, computer models for estimating life cycle costs have been developed and applied to track maintenance decisions [Veit, 2000; Levi, 2001; Danzer, 2000; Zoeteman, 1999a and 2001]. Serious feasibility studies for computer-assisted work planning are currently in progress at for instance *Railtrack* and the Dutch Infrastructure Manager, *Railinfrabeheer*. However, these tools are still in an early phase of development and there are hardly any examples of their successful implementation in the decision-making processes. The development of the *asset register*, for instance, took *Railinfrabeheer* a couple of years, and it is still proving to be very hard to link the data as mentioned above [Gerritsen, 2001].

However, due to increasing pressure from government and operators to reduce budgets and track possession time, it is essential to improve the quality and transparency of design and maintenance decisions more quickly. An approach is needed that can support decision-makers adequately in the absence of these tools. In this paper the concept and use of a decision support system (DSS) based on Life Cycle Costing (LCC) is discussed, which should assist

decision-makers instantly in analysing the expected infrastructure costs and performance [Zoeteman, 1998].
LCC provides the theoretical concepts needed to balance short-term and long-term costs and performance (revenues). 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 [Stephen and Dell'Isola, 1995].
The Life Cycle Costing approach has been applied in five different cases up to 2001. In this paper theory (section 2), design (section 3) and an application (section 4) of the approach will be presented. The application illustrates the decision support provided to an international consortium during the tender for the Dutch High-Speed Line South and focuses on the design of the railway tracks. Finally, section 5 contains the conclusions.

2. A framework for analysing the long-term performance

Design and maintenance decisions can only be taken responsibly, when the costs and performance of decision alternatives are considered on a long-term, life-cycle basis. This also includes the delivered availability and reliability, since the infrastructure performance influences the costs and revenues of the operations. In this section Life Cycle Costing theory is discussed and operationalised for the rail infrastructure environment.

2.1 Life cycle costing

According to LCC, the course of action should be taken that results in the lowest total costs over the life span of a production facility, in this case the railway system. Decisions taken during the design, construction, maintenance and operation of a railway line can have an impact on the costs and revenues during the residual economic life. In order to make these costs and revenues comparable, i.e. to express them in equivalent currency units, the cash flows occurring during the analysed life span are discounted to a Base Year, in which the decision is being made. Discounting is used to include interest payments and incomes: in other words, for a Euro spent in 2001 more interest has to be paid than for a Euro spent in 2010, which can be saved in the bank until expenditure. A *real interest rate* is applied, which excludes the annual inflation rate [Sugden and Williams, 1978]. Cost estimates have to be based on the cost rates in the Base Year as well.
In LCC theory the *life cycle costs*, the total costs of ownership and operation, are the criterion used to assess alternative courses of action, i.e. different physical designs or maintenance strategies. There are three different ways to present these costs:

- The *total present value* (TPV) is the sum of all discounted cash flows. In the LCC method it mostly concerns costs; incomes can be expressed as negative costs. The larger the TPV, the less attractive the investment compared to alternative investments or maintenance strategies.
- The *internal rate of return* (IRR) shows the profitability of an investment compared to alternative investments or maintenance strategies.
- The *annual equivalent* or *annuity* (ANN) is the sum of interest and amortisation, which has to be paid every year to finance the investments and maintenance. With the annuity, projects of different life spans can be compared.

In order to make a correct decision, all costs (and revenues) *affected by the decision* should be considered. These costs can be categorised as follows [Flanagan and Norman, 1983]:

1. *Tangible and intangible costs.* Tangible costs are paid ‘out-of-pocket’, for example, the costs of construction and maintenance (labour, materials and machines). Intangible, hidden costs, which are not directly paid by the perpetrator, are the result of quality loss, reduction in transport services, reduced safety and comfort levels, and noise nuisance. These costs are to be reflected in performance regimes and maintenance standards.
2. *Initial (capital) costs and running costs.* The initial costs are the costs made for acquisition and installation or construction. The running costs are made during the operational period of the railway. A further distinction can be made between annual costs, such as inspections and small maintenance, and intermittent or periodic costs, such as major overhaul and renewals.
3. *Costs of ownership and costs of operation.* In a cost breakdown a distinction can be made between the costs suffered by the infrastructure owner, usually the central government, and the costs suffered by the operators.

LCC theory presumes that if all these costs are identified for all courses of action, the course of action with the lowest life cycle costs should be chosen. A prerequisite for the comparison is that the solutions provide the required service and technical standards (e.g. design parameters for a high-speed line are much stricter than those for a conventional line).

In practice other factors will also influence a decision. Other criteria than life cycle costs will play a role in decision-making processes. Regulations related to safety, noise and vibrations, riding comfort, and labour conditions are obvious constraints to be considered in the development of decision alternatives. Further, the available budget can for instance urge the IM to opt for a design with lower construction costs. However, even if the budget is a serious constraint, the assessment of different alternatives still enables the decision-maker to select a second-best alternative with the *less worse impact* on life cycle costs. LCC is thus considered an adequate approach to increase the quality of design and maintenance decisions: it can mobilise state-of-the-art knowledge in order to lay down assumptions about future maintenance in a transparent way. Decision-makers are able to choose a design or maintenance strategy with the best guarantee of being the most cost-effective and assumptions can be monitored systematically in order to further refine design and maintenance strategies.

An important issue is the reliability of data used for estimating maintenance needs and failure rates. Assumptions have to be made about the future operational conditions of the railway line and the deterioration of the railway assets. The design or maintenance solution should be robust, i.e. remain the preferred alternative under varying conditions, such as more/less transport than expected, a higher/lower interest rate and a quicker/slower asset degradation. Basically two methods can be used to test the robustness:

- *Sensitivity analysis.* In sensitivity analysis the input values are systematically varied, with percentages of plus/minus 10%, 20% and 30%. The most sensitive input parameters are identified by the deviation percentage of the outcomes. It is important to get an accurate estimate on the likely value of these variables. A disadvantage of a sensitivity analysis is that usually only one variable at a time is tested and possible interactions between the factors are therefore not directly revealed [Flanagan and Norman, 1983].

- *Uncertainty analysis.* If the life cycle costs are determined by several risky variables, sensitivity analysis might be insufficient. *Uncertainty analysis* is a more sophisticated approach, where the input parameters of a model are considered to be random variables, from which samples are drawn. Monte Carlo simulation is a powerful technique to approximate a normal (probabilistic) distribution of the outcomes: the chance of a specific outcome can be deduced for a set level of confidence [Flanagan and Norman, 1983]. Uncertainty analysis is also discussed in, for example, Chessa *et al*. [1999].

2.2 Life cycle costs of rail infrastructure

In order to be able to estimate life cycle costs, the factors influencing the performance of the railway infrastructure have to be identified as well as their relationships. The driving factor causing maintenance and failures is the degradation of the asset. There are different degradation modes: electric equipment can for instance fail instantaneously, whereas assets that wear due to mechanical contact, such as the wheel/rail-contact, degrade gradually. In Figure 1 a theoretical degradation pattern is shown for a specific track parameter named 'roughness'. With the amount of tons carried by the track, measured in million gross tons or MGT, the roughness of the track increases (or: the track condition decreases) and rehabilitation is needed.

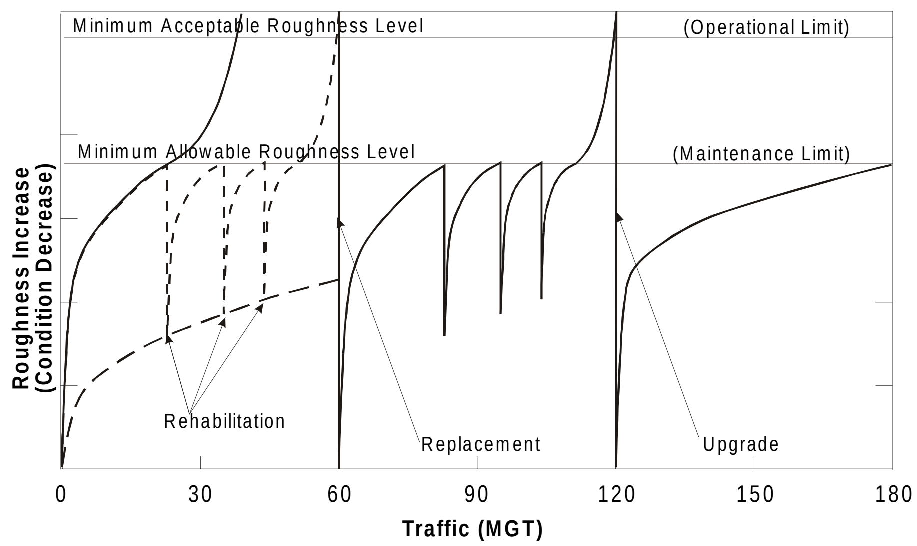

Figure 1. Hypothetical degradation curve of track geometry [Ebersohn and Ruppert, 1998]

The Infrastructure Manager applies a Maintenance Limit (or threshold) based on its experience that the deterioration will be progressive once the limit is passed. The dotted line shows that a replacement of the track can be postponed by timely maintenance. After some time the effectiveness of maintenance has become too low (decreasing maintenance interval) and a replacement is required. This replacement should be planned before the track condition passes the Operational Limit, which is set to guarantee the safety and reliability of rail transport.

Another example of a maintenance decision is shown in the same figure: once the limit of 120 million tons is passed, the Infrastructure Manager upgrades the track structure with e.g. a ballast bed of a higher quality. This results in a lower rate of degradation and less maintenance. The improved track quality and reduced amount of maintenance should be traded off against the extra investment to be made.

Track degradation depends on all kinds of factors, such as the initial quality of construction, the quality of the substructure (e.g. settlements and crushing of the ballast bed), and the loads on the track. Historic data can provide insight into the actual decline rates and the effectiveness of maintenance activities under specific conditions [Ohtake *et al.*, 1998; Zaalberg, 1998].

Besides asset degradation, there are other factors that also influence the life cycle costs, such as the RAMS standards applied, the amount of preventive maintenance (rehabilitation), market prices for labour, materials and machines, and the operational characteristics of the line (such as axle-loads, traffic intensities and the duration of train-free periods). The Infrastructure Manager can manage some of these factors directly (e.g. maintenance strategy) or with the co-operation of transport operators (e.g. quality of rolling stock) and government (e.g. negotiated grant). Exogenous factors, such as the condition of the soil and the interest rate, will also influence the life cycle costs.

In Figure 2 a conceptual model is presented, which is discussed extensively in Zoeteman [2000a]. The performance of the railway infrastructure is defined in this figure as the level of safety, riding comfort, noise, vibrations, reliability, availability, and the costs of ownership. Safety and noise standards indirectly influence the life cycle costs, since they determine the tolerances and thresholds for design and maintenance parameters. Other functional parameters, like maximum speed, minimum headway and maximum axle-load supported, constrain the feasible design or maintenance strategies as well.

The physical design directly determines the costs of ownership (amount of investment). This investment is also determined by, for instance, the accessibility of the construction site. The design also influences the asset degradation (initial quality) together with other conditions, such as traffic intensities and axle-loads, the quality of the substructure and the effectiveness of performed maintenance.

The quality degradation determines the required volume of maintenance and renewal (M&R). The chosen maintenance strategy influences the amount of preventive and corrective M&R over the life span. A factor that determines the M&R volume as well is the annual budget available for M&R: a backlog in M&R can result in a more rapid decline of the quality of the infrastructure. The realised M&R volume causes expenditures and planned possessions (reduced availability). Besides, the maintenance strategy also has a direct impact on the life cycle costs through the costs of the organisation for restoring failures (*incident management*).

Subsequently, the incident management organisation, the realised M&R volume, and the transport concept, which includes the track layout, determine the train delay minutes caused by infrastructure failures (reduced reliability). If applicable, the delay minutes may be converted into penalties for the Infrastructure Manager using a *Performance Payment Regime*. Finally, the performance penalties, the maintenance and renewal costs, and the construction costs make up the total costs of ownership.

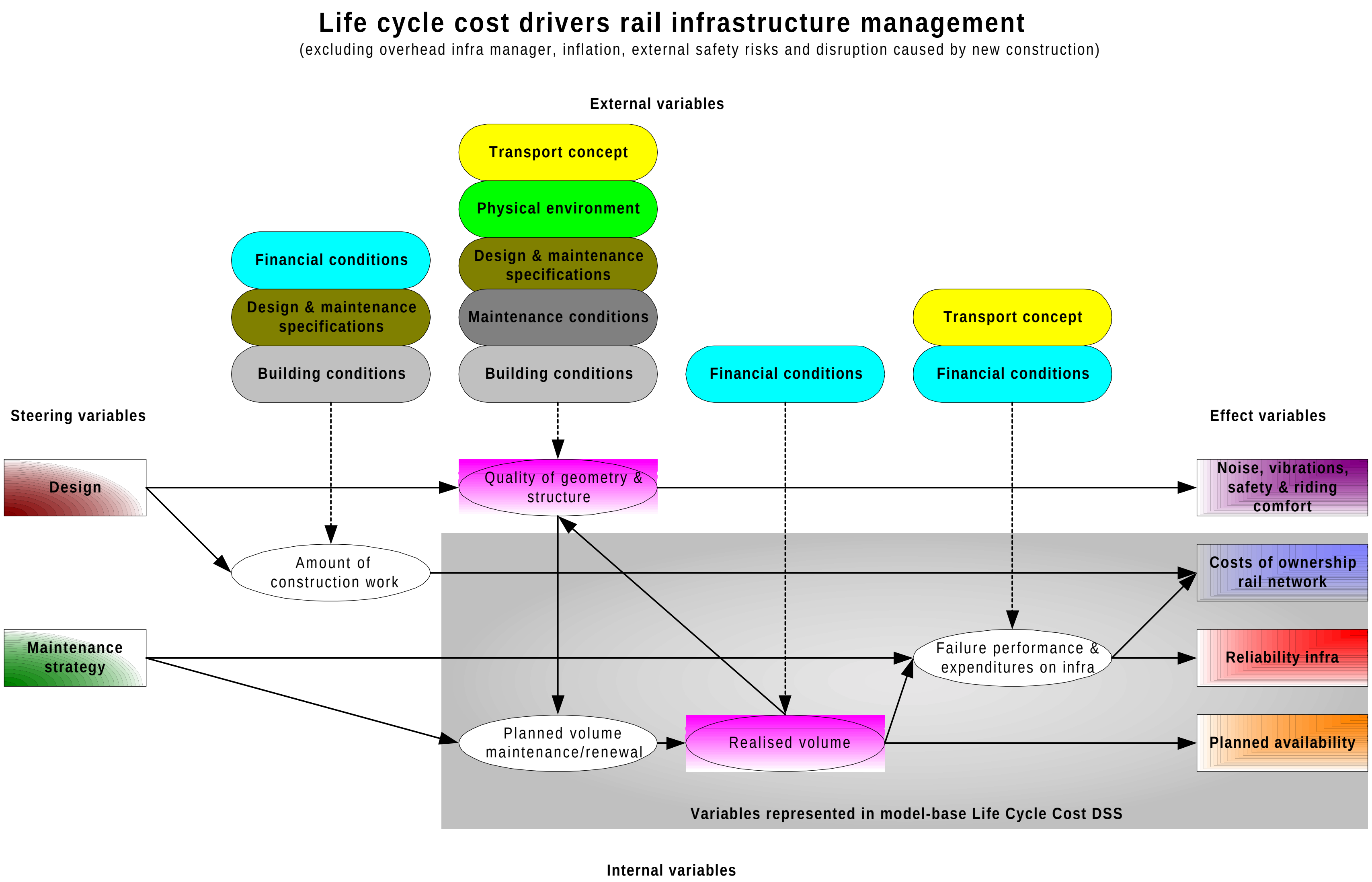

Figure 2. Factors influencing the performance of rail infrastructure

3. A decision support system for estimating life cycle costs

3.1 Supporting decision-making on design and maintenance

The previous section describes the relationship between the core products of the Infrastructure Manager's strategic decision-making, design and maintenance strategy, and the infrastructure performance in terms of life cycle costs. It is obvious that more insight is required in the actual (strategic) decision-making process in order to be able to support the process.

Design and maintenance used to be strictly separate processes in the state-owned railway companies. This was also the case for the different technical disciplines such as track, power supply and signalling. Within these "islands" in the hierarchical organisation skill-based staff were responsible for the operational and tactical decision-making [Swier, 1998]. Decisions were based on the tacit knowledge of these experts and detailed procedures and technical standards, prescribing the design parameters and maintenance frequencies. Decision-making had a strong technical focus, driven by the railway safety which always had to be guaranteed.

The restructuring of the railways has led to new questions for the Infrastructure Managers, which were discussed in section 1. The technical standards and procedures for the underlying design and maintenance processes have not become superfluous, but the performance demands of governments and Transport Operating Companies has led to functional specifications, such as levels of reliability, availability, and maintainability. A strategic level of decision making is needed, surpassing the technical design and maintenance processes, where physical designs and maintenance strategies are selected based on the required performance. This level of decision-making was blurred and ill-developed, as the developments discussed in section 1 showed. Nevertheless, based on maintenance management theory and the tender for the Dutch High-Speed Line (HSL), a model of strategic decision-making for design and maintenance can be drafted [Wilson, 1999; HSL South Project Organisation, 1999a and 1999c].

During the first step the required functionality and performance are determined. Based on the expected transport demands and a global analysis of the quality of the existing infrastructure and available technology, a level of performance has to be determined which satisfies the demands. This step is usually performed by the Government and is especially applicable for new infrastructure and upgrading projects or for developing performance agreements for existing railway networks. Products of this step are functional specifications, such as required reliability and availability, and a Performance Payment Regime (PPR) for the Infrastructure Manager, whether it be a public or private company. During the second step, for instance the Consultation Phase of the Dutch HSL, the (potential) Infrastructure Manager studies the consequences of the functional specifications in detail. Reliability and costs of available technology and the significant conditions for financing, construction and maintenance are identified. Products of this step are a feedback on the feasibility of the delivered performance requirements (global cost consequences) and a first list of possible design or maintenance alternatives. During the third step an extensive, quantitative performance analysis of the feasible alternatives is performed. Expectations on construction costs, maintenance needs and failure rates are made in order to estimate the life cycle costs for the management period considered. Products of this step are a short-list of attractive decision alternatives, with their life cycle cost estimates and a specification of the risks. Again, this can deliver new suggestions for modifying the performance requirements when they cause disproportionately high risks or costs. During the fourth step a choice is made to implement a specific alternative based on the risk preferences of the Infrastructure Manager and its lenders, and the agreed allocation of risks between Government and Infrastructure Manager. During the fifth step a detailed design or maintenance strategy is developed, usually by the Infrastructure Manager and its contractors.

A more detailed analysis of the decision-making processes on design and maintenance can be found in Zoeteman [2000a].

During each of the steps of the decision-making process the decision-makers have the need to get a quantitative insight into the impact of a specific decision on the life cycle costs. As Figure 2 showed, the life cycle costs are the result of a complicated set of (partly uncertain) conditions. The number of factors affected and the uncertainty involved necessitate an analysis of different scenarios (future conditions), in which the concept of a decision support system (DSS) can eminently contribute.

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 [after Van der Heijden, 1986]. A DSS usually consists of a database, a model-base (containing the models that use the data to produce the output), and a user-interface [Bidgoli, 1989; Finlay, 1994].

With its capability to estimate life cycle costs of different designs, maintenance strategies and operational conditions, the DSS can assist in reaching several goals, which are:

- evaluating different physical designs or maintenance strategies in order to select the most robust, cost-effective solution in a systematic and transparent way;
- analysing the impacts of (restrictive) operational and financial conditions for maintenance of the assets in order to discuss them with other stakeholders;
- supporting the development of maintenance plans that aim at optimising the life cycle costs of the rail system;
- training technical and financial staff in optimising design and maintenance decisions.

In the case of this DSS, ‘chauffeured system use’ is applied: a specialised analyst functions as an intermediary between the computer model and the decision maker.

The outputs of the DSS are estimates on total costs of ownership during a specified period (life cycle costs) and estimates on reliability and availability of the system. In Figure 2 the relationships in the grey area are modelled within the DSS. Budget limits are not a constraint modelled in the DSS: it is the responsibility of the user to select those decision alternatives to be analysed which are feasible, also considering the available budget for construction and maintenance. In section 3.2 the data required and the models used are described.

3.2 Description of the DSS and the data collection process

The final outputs – life cycle costs, reliability and availability – are calculated in a number of steps, according to Figure 3. In this figure the calculation processes are shown as rectangles. On the left and right side the data needed for the calculations are shown. 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.
In addition to the DSS, a Data Collection Checklist, which exactly describes the input data and data formats, and a number of Chauffeured Sessions for data collection and validation should increase the reliability and the robustness of the analysis as well as the support among engineering staff and responsible managers.

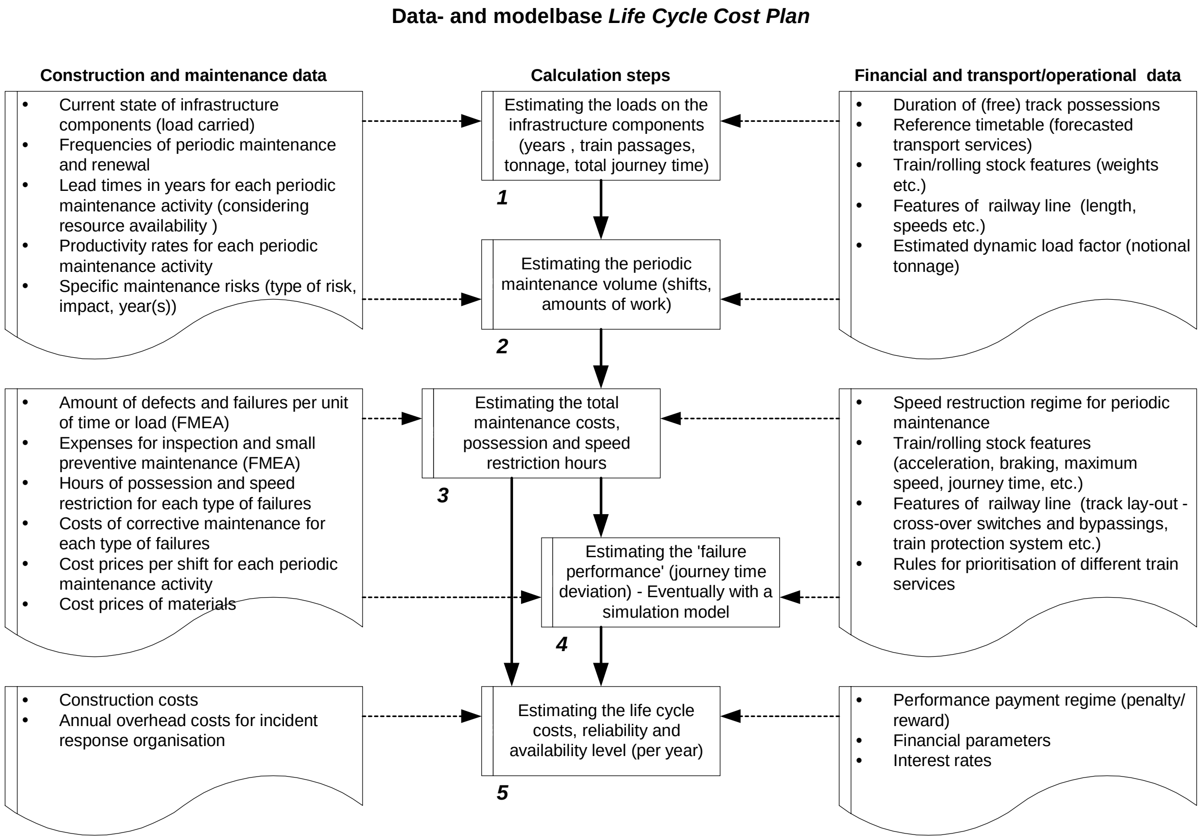

Figure 3. Structure of the 'Life Cycle Cost Plan' *decision support system*

The data tables are reflected in a Data Collection Checklist. Many data sources can be used, such as empirical data (e.g. laboratory tests, computer simulation, supplier information, maintenance history and actual maintenance cost rates) and 'expert judgements' on e.g. the number of failures expected. Since maintenance analysis and planning tools have become available only recently and on a limited scale in the European railways, data on failures, track degradation and work history are hardly available or reliable. A lot of measurements on the infrastructure quality were made in the past, but mostly for operational use e.g. for identifying bad spots that needed maintenance urgently [Esveld, 1989]. Especially degradation of infrastructure components is a complicated process. The aim of the DSS is *not* to develop predictive models for asset degradation, but to use the output of these models, if available. Developing these types of models is part of large research projects with lead times of many years. A lot of input data of the DSS, therefore, depends on expert judgements.
The reliability of data is taken care of in two ways. First, Chauffeured Sessions are organised in a similar way to Delphi-studies for technology assessments [Sackman, 1975], with the

difference that the experts meet each other directly. In the Chauffeured Sessions a process of data collection and validation takes place. Depending on the progress, the input data itself is discussed, the DSS is used to show *on-line* the impacts of assumptions, or the likelihood of the output (*face validity*) is discussed. Participation of experts from, at least, different organisational units is a prerequisite for the quality of the process (not a guarantee, however). Moreover, each of the participants has to make their judgements on the input parameters prior to the session. During the sessions these judgements are discussed and the participants get the opportunity to adjust their judgement or to come up with new information. In most cases discussion results in one judgement; however, it is also possible to test a range of judgements in the DSS. The Data Collection Checklist and the Chauffeured Sessions should guarantee that the modelling assumptions are well known and are made in an unbiased, reliable way.

Secondly, the robustness of the outcomes can be analysed with the DSS itself using sensitivity analysis. The importance of a specific input variable for the overall outcome is revealed as well as the robustness of the decision alternatives: if alternatives change in rank (based on level of life cycle costs), some of them are less robust than others.

Below the calculation processes are described. Some graphical output screens are added to give an impression of the intermediate results. The figures are for illustration purposes only, since it would consume too much space in this paper to discuss the example data used to produce these figures.

Calculation Process 1: Estimating the loads on the infrastructure

Quality degradation is a function of time (years) and load on the track (cumulative gross tons[1] or number of train passages). As Figure 2 showed, a lot of factors influence the degradation. However, most of these variables influence the degradation *rate* (loss of quality per unit of time or load). This degradation rate per infrastructure component is reflected in the tonnage- or time-based maintenance threshold. As an example, applying a heavier rail type can reduce the wear rate. If wear is the determining factor, mostly in curves or on sections with heavy axle-load operations, a heavier rail can carry more tons. A higher threshold, in this case for *tons carried before replacement*, is set to reflect the lower degradation 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 on the line 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. This timetable is also used for calculating the (annual) scheduled journey time. This is the sum of the journey times for all trains on the particular track section. *Performance regimes*, such as for the High-Speed Line South, can use this as a basis for the calculation of the reliability level. The timetable also reveals the time available for track possessions that do not affect the quality of the transport services.

Calculation Process 2: Estimating the periodic maintenance volume

The second step consists of an estimation of the periodic maintenance (major works, such as rail grinding and track tamping, with intervals of more than a year). Thresholds for each

[1] In tonnage calculations a gross notional tonnage can be used according to UIC leaflet 7.14. This internationally developed and applied formula makes it possible to compare railway lines where different speeds, axle-loads and wheel diameters are used.

major maintenance activity are specified as well as the current loads carried. The residual life spans and thus the moments for major overhaul or renewal are deducted for each infrastructure component. Besides, it can be set to realise the work during a couple of years (instead of a single year). Further, the decision-maker can label very unlikely activities of which the possible impact should be studied as *specific risks*. Their contribution in the life cycle costs is shown separately. Finally, the number of shifts is calculated based on the productivity rates for each activity (net productivity, set-up and finishing time). In Figure 4 the graphical output of the second calculation step is shown.

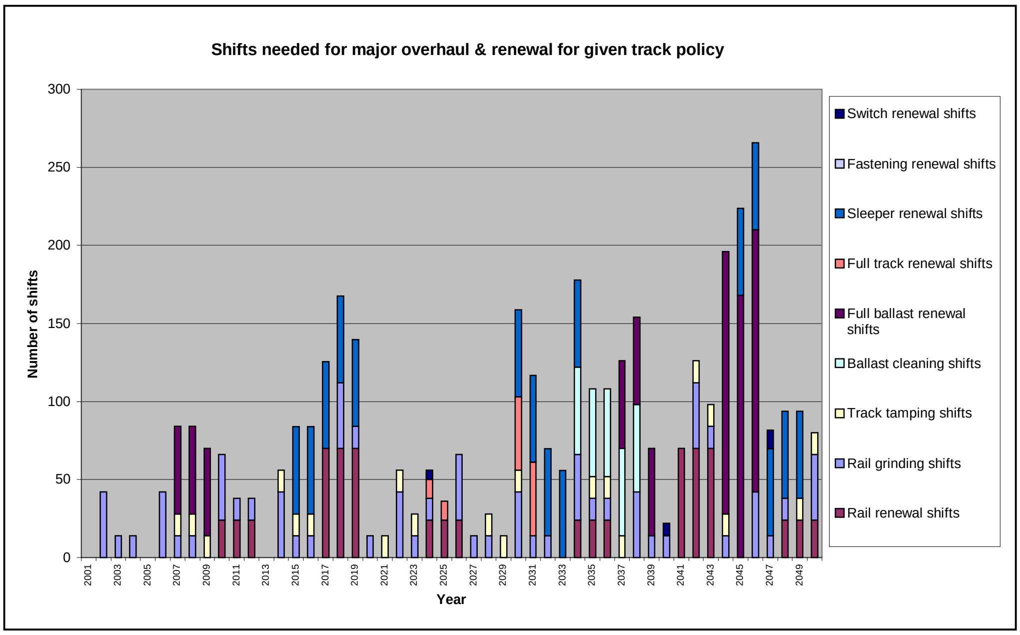

Figure 4. Planned work shifts, intermediate result after step 2

Calculation Process 3: Estimating the total maintenance costs and 'possession hours'

Based on the number of possessions per year the total costs for periodic maintenance can be calculated based on the costs per kilometre (materials) and a cost per work shift (labour and machines). A number of days with speed restrictions can be set, if applicable. The total hours of possession and speed restriction are estimated in this way.

In step 3 the amount of small maintenance and number of failures are calculated as well.

Small maintenance and failures are simply related to the cumulative tonnage or in-service years of the component. The user can set the costs per ton or per year for inspection, small maintenance and failure repair. The small maintenance and failure repair consists of many different tasks, which is why the summarised estimates (costs, possession and speed restriction hours) are used. Failure Mode Effects Analysis (FMEA) is the technique to be used for estimating the amount of small maintenance and failures. Figure 5 gives an impression of the output of step 3.

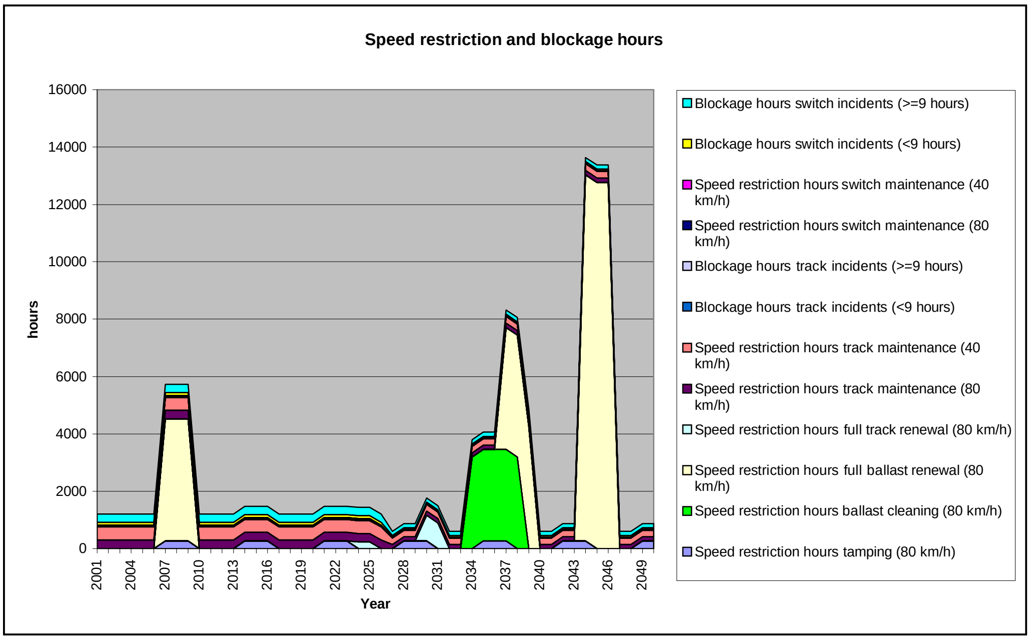

Figure 5. Planned and unplanned disruption, intermediate result after step 3

Calculation Process 4: Estimating the failure performance

In some cases Infrastructure Managers are penalised or rewarded for their performances based on the delay minutes caused by failing infrastructure assets. Depending on the details of such a Performance Payment Regime (PPR), a final sub-step is the conversion of speed restriction and unplanned possession hours to expected train delay minutes and cancellations. A model can be included that estimates the cumulative train delay minutes and cancellations, based on the acceleration and braking performance of the trains and a number of assumptions on the impact of a speed restriction and full track blockage. In such a PPR train cancellations count for a (large) number of delay minutes. Dividing the total delay minutes by the total scheduled journey time in the specified time interval delivers the 'unreliability' of the infrastructure[2]. A more advanced analysis of the 'knock-on impacts' of delayed trains on later scheduled trains may be done with for instance Simple++, a dedicated simulation model such as RailSys [Rudolph, 2000], or using an analytical method [Goverde *et al.*, 1998]. For instance the location of cross-over switches and the number of train services can influence the cumulative delay minute. In some PPRs also the possession time for planned maintenance have to be paid. Costs of possessions and penalties are calculated.

Calculation Process 5: Estimating the life cycle costs

In the last process the total costs of ownership (life cycle costs), and the reliability and availability estimates are made. If applicable, the construction costs are included in the total cash flows. Another choice is to include or exclude the *specific risks*. Finally, the costs of

[2] Sometimes the terms 'availability' and 'reliability' are confused. Unavailability also includes planned possession time for maintenance. Unfortunately the term 'availability' is used in the PPR of the HSL South, presented in section 4 where 'reliability' is meant. Track possessions during night are for free use according to the PPR of the HSL South.

financing are calculated based on the interest rate. The life cycle costs of the different design or maintenance solutions are presented as the *performance fee*. The performance fee is the annuity (annual flat fee) that has to be paid every year during the analysed period for financing the solution (interest and depreciation). If a PPR is applied, penalties (and eventually rewards) are included in the fee. Figure 6 gives an impression of the outcome of step 5.

For each calculation process a model is used that consists of a set of equations. In table 1 an example is given of some formulas to calculate the performance fee needed to finance the periodic maintenance, excluding the consequences for transport services. Based on a passed threshold, maintenance is initiated for a certain part of the infrastructure component. The number of shifts depends on the duration of a single track possession and the productivity rate of the particular maintenance activity. The costs are calculated with unit costs per shift (labour and machines) and per kilometre (materials)[3]. Finally, the annuity of all periodic maintenance expenses, scheduled during the analysed period, is calculated.

Thresholds can be interdependent: renewals can be clustered in time and place (clustering of renewals on adjacent track sections or of different infrastructure components). Besides, it is well possible that a particular maintenance activity harms the condition of another component (e.g. the ballast bed quality can degrade as a result of tamping the track). If these formulas are to be applied in a DSS model, such relationships should be considered.

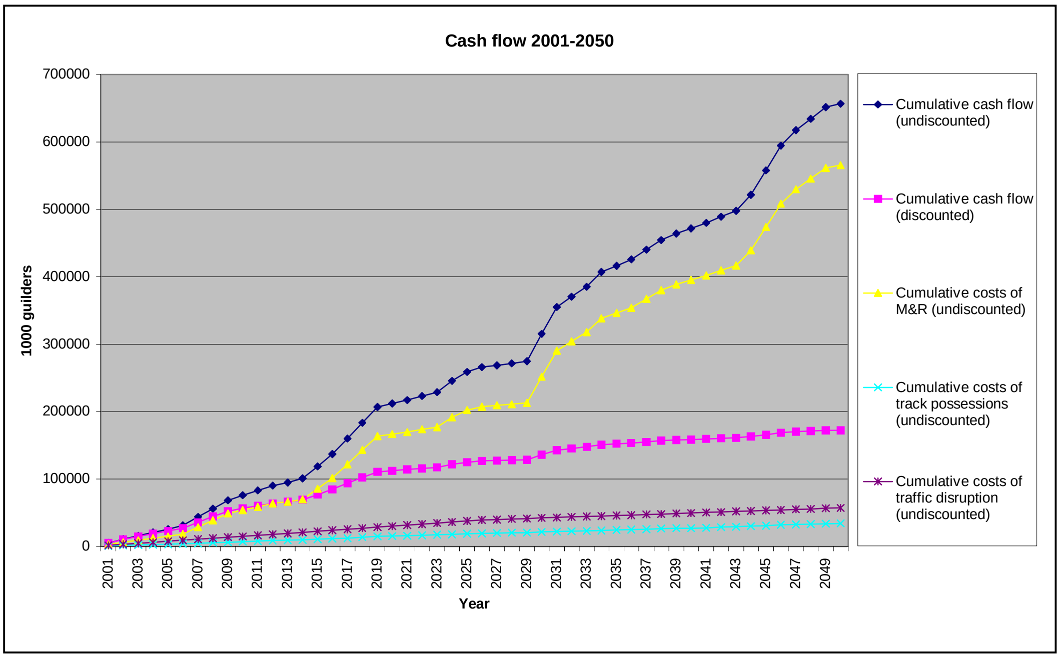

Figure 6. Cash flows during the period of analysis, intermediate result after step 5

[3] A maintenance shift is a co-ordinated work, which takes place during a track possession on a certain location on the railway line.

Table 1. Simplified formulas for calculating the annuity of renewals

Nr.	Formula	Explanation
1	$RQ_{y,a} = Q_a \bullet P_{y,a}\left(T_f \geq TH_a\right)$	The quantity of periodic maintenance, *RQ*, in a particular year (y) for the analysed activity (a) is determined. The quantity *Q* is for instance the total track length or number of switches. *P* is the part of the asset(s) to be renewed given the fact that the notional tonnage (T_f) has passed the threshold (*TH*). E.g. if *P* is 0.50 for rail renewal, half of the total number of track kilometres needs to be rerailed.
2	$S_{y,a} = roundup\left(\frac{RQ_{y,a}/PS_a}{TPP_y - L_a}\right)$	The number of hours needed for the periodic maintenance is determined by the production speed (*PS*). The hours have to be scheduled according to the duration of a track possession period (*TPP*) provided. For each *TPP* also time is lost due to set up and finishing of the work (*L*). The total number of shifts *S* is calculated (whole number).
3	$C_{y,a} = SC_x(TPP_y) \bullet S_{y,a} + RQ_{y,a} \bullet (MC_a - RV_a)$	The costs for periodic maintenance are calculated by multiplying the number of shifts with the costs per shift (*SC)* for the given duration of the track possession *(TPP)*, and by adding the material costs (using the unit costs, *MC*, and the residual value per unit *RV*).
4	$TPV = \sum_a \sum_{y=0}^{n} \frac{C_{y,a}}{(1+i)^y}$	The total present value *TPV* is the sum of the discounted costs *C* during all years (*y*) and for all activities (*a*) analysed. Year *n* is the last year, i.e. the time horizon of the analysis. The interest rate applied is *i*.
5	$ANN = \frac{(1+i)^n \bullet i}{(1+i)^n - 1} \bullet TPV$	This formula is used to convert the total present value of the investment or maintenance strategy into the annuity (*ANN*) or *performance fee*.

4. Case: Evaluating track designs for the High-Speed Line South

In 1999 the Life Cycle Costing approach was used to support an international consortium in evaluating different track designs for the High-Speed Line South. The High-Speed Line South (HSL South) is the Dutch part of the high-speed link from Amsterdam to Brussels, Paris and London. In 2005 the operations, both domestic and international, on the HSL South should commence. The new tracks, with a total length of almost a hundred kilometres, will be designed for 300 km/h. In fact it consists of two different sections, since the trains will use the conventional network at Rotterdam. For the northern section in particular considerable investments will be made for the substructure: a piled concrete slab structure will support the rail system. The civil works and the infrastructure for connecting the HSL South to the conventional network are geographically split up into six contracts. The rail system, i.e. tracks and switches, power supply and signalling systems, electrical and mechanical (auxiliary) equipment, and the sound barriers, has been tendered as a whole in the so-called *Infrastructure Provider Contract*.

The Infrastructure Provider (IP) has the obligation to Design, Build, Finance and Maintain (DBFM) the rail system. During the first 25 operating years the Dutch State will pay a fee to the IP. After that the infrastructure is transferred to the Ministry of Transport with a guarantee period of five years for backlogs in maintenance. The IP will be penalised for a shortfall in performance: for a low asset condition and especially for train delays and cancellations so-called non-availability deductions will be made. The calculation of the penalties is based on a Performance Payment Mathematical Algorithm (PPMA) [HSL South Project Organisation, 1999a].

Since the consortia already had to submit their bids in 2000 without knowing the exact traffic conditions, the Dutch State had developed a so-called *Reference Timetable*. This timetable contains the forecasted trains for the years 2005-2029, completely specified as a timetable. This hypothetical timetable will be used to calculate train delay minutes and cancellations caused by infrastructure failures.

One of the important issues during the Consultation Phase in 1999, has been the selection of a railway track structure, especially since the Ministry of Transport put forward that innovative, slab track systems should seriously be considered [HSL South Project Organisation, 1999b]. In the engineering team of the Consortium several promising track structures were selected, such as conventional ballasted track, the German Rheda system, the Japanese Shinkansen Slabs, a Direct Fastening system and the Dutch Embedded Rail Structure (see Figure 7).

Figure 7. From left to right: Ballasted Track, Shinkansen Slabs, and Embedded Rails

During the first months of the Consultation Phase, in which the State consulted the Consortium on the track design to be most applicable, qualitative judgements like ‘well maintainable’ or ‘low availability’ prevailed. However, a quantitative insight was needed to find an answer to the following questions:

- What are the costs and performance using different designs?
- What is the impact of different interest rates?
- What is the impact of the number of trains on costs and availability?
- What is the impact of the Performance Payment Regime for different track designs?

- What is the impact of speed restrictions? What is the impact of the provided duration of maintenance slots (free possessions) in the Reference Timetable?

For this purpose a twofold analysis process was initiated [Zoeteman, 1999b]:

1. A Failure Mode Effects Analysis (FMEA) was organised to assess the different track structures. In the FMEA all probable failure causes, modes, measures for prevention and monitoring, and their effects were identified. A distinction was made between immediate failures and loss of quality (speed restrictions) that could be restored during nightly track possessions. Sessions were organised to collect expert judgements, while some data was available from international investigations. Some of the slab track types are rather innovative and maintenance experiences are limited.
2. The decision support system, *Life Cycle Cost Plan*, was modified in order to include the Performance Payment Mathematical Algorithm (PPMA) for the HSL South, the Reference Timetable and other parameters of the HSL South system. Once available, the expectations from the FMEA were used as input for the analysis of the life cycle costs with the DSS. The robustness of the outcomes for the different track designs was tested. The outcomes were used to support discussions with the Ministry of Transport as well as to (pre)select the most cost-effective track structures.

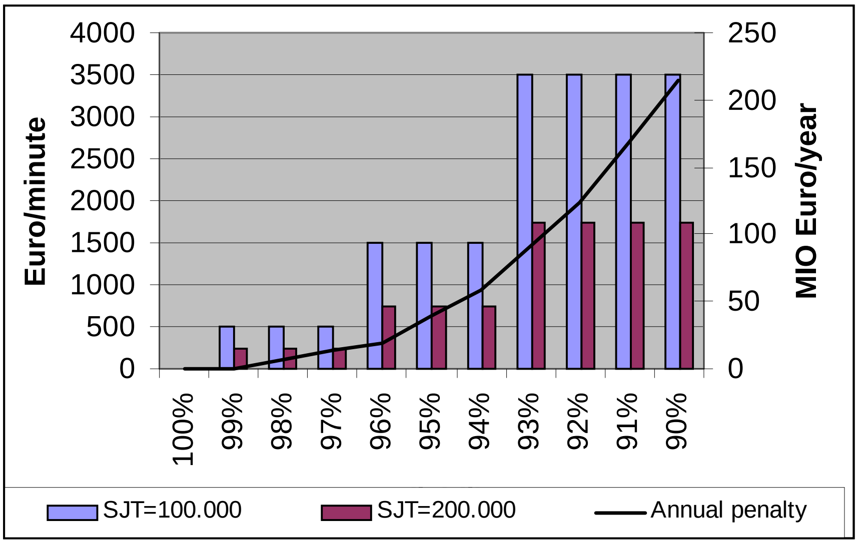

Figure 8. INDICATIVE performance penalties for an annual flat availability level
The bars indicate the penalty rate per minute for a given scheduled journey time during four weeks (SJT). The curve indicates the resulting total penalty per year

An important finding was the high sensitivity of the outcomes for different availability levels of the system. If in a specified *performance period* the train delay minutes increase, the penalty rates increase as well, which causes a progressive trend (see Figure 8). This made it also necessary to simultaneously get insight into the influence of the signalling and power supply systems on the total system availability[4].

[4] If signalling and power supply systems cause already a certain amount of non-availability, a track design with a lower performance will result in disproportionately higher penalty costs.

Figures 9 and 10 give an outcome for a design with ballasted track without so-called ballast mats. The relative low construction costs in combination with the large amount of maintenance in the last contract years prove to have a beneficial impact on the required performance fee, in contrast to the more expensive, low-maintenance slab tracks. The Infrastructure Provider can save money in the bank, which is needed to finance maintenance works by the end of the contract. The 'short' management period, compared to the life-cycle of the track structure, and the requirement of private financing reduce the attractiveness of the innovative slab tracks.

It must however be noticed that the positive outcome for ballasted track (required performance fee) is greatly reduced for design variants that include the use of ballast mats. Later during the design process these rather expensive mats were considered to be unavoidable in order to minimise the risk of ballast renewal. Ballast mats dampen the loads from the ballast bed and reduce the friction between the ballast bed and the concrete substructure. An early degradation of the ballast bed and thus a ballast renewal would be a great risk to the Infrastructure Provider, since it involves a lot of costly maintenance works and speed restrictions.

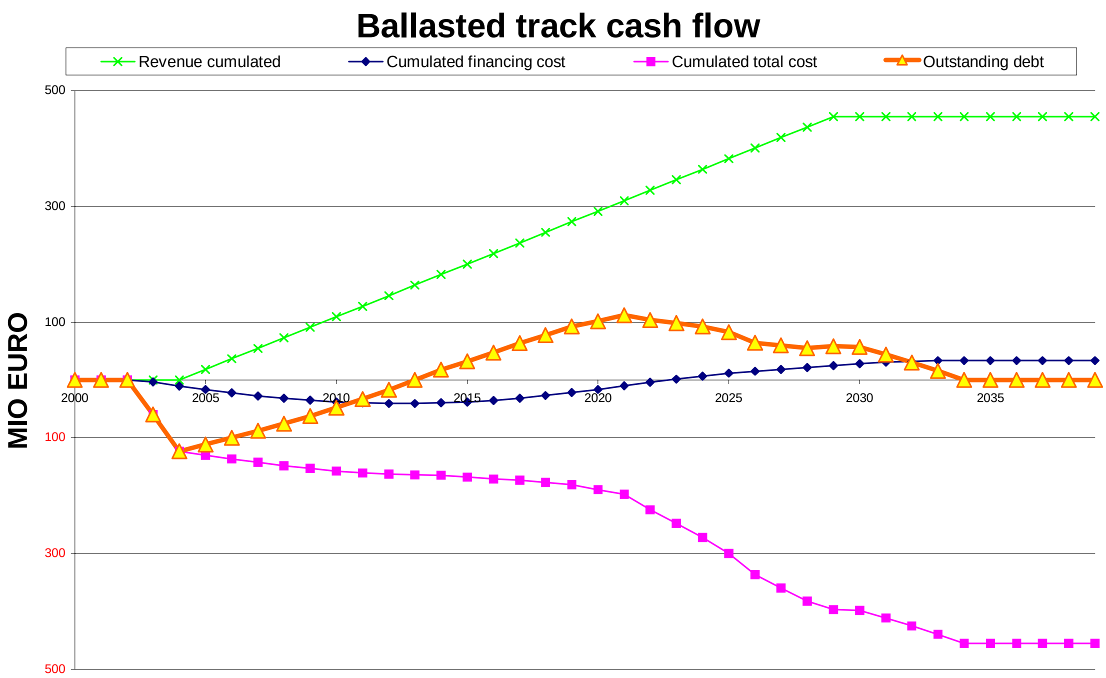

Figure 9. Cash flow for a track structure (for illustration purposes only)

Finally, based on the life cycle cost analysis two attractive track structures have been chosen for a detailed design during the Tender Phase. Due to some uncertainties, such as renewal thresholds for the innovative track designs, not all differences of opinion could be resolved [Zoeteman, 1999b]. Afterwards, interviews were held with all decision-makers and technical experts that participated in the process in order to evaluate the effectiveness of the decision-support [Zoeteman, 2000b].

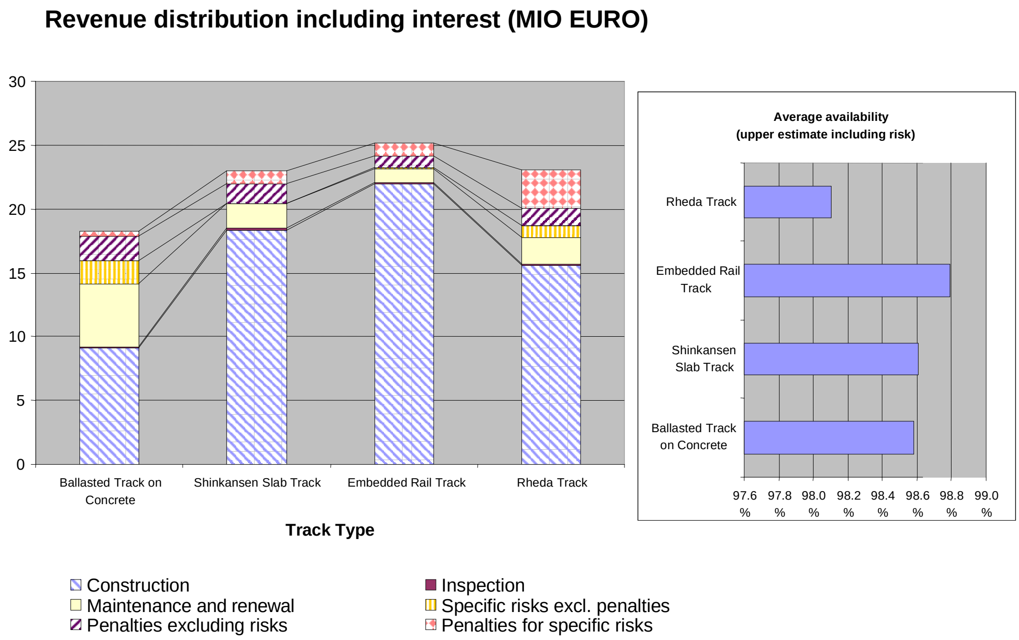

Figure 10. Performance fees for a specific scenario (for illustration purposes only)

The strength of the use of the DSS proved to lie especially in improving the *manageability* of the analysis of reliability, availability and life cycle costs. Using the DSS was considered to be helpful in gaining insight into the complicated factors influencing the costs and performance of the different track designs. The DSS also proved its value in increasing the sense of urgency among decision-makers and technical experts that this insight was essential. For instance, it clearly showed the huge impact of the Performance Payment Regime on the costs to be covered by the Infrastructure Provider (penalties) and thus the importance of a well-considered design and maintenance strategy. Other positive scores related to the insight provided in the consequences of different future conditions (scenarios) and the fact that the analysis led to a greater number of decision alternatives that was seriously considered. Less positive scores were related to the ability of the DSS use to change the perception of the actors involved and to increase the commitment to a specific alternative. A deficiency of the approach followed in this case study was that the data collection and validation sessions were not well-implemented. This can partly be explained by the fact that not all actors in the particular consortium were participating fully in the analysis and decision-makers were under pressure to meet deadlines set by the Government [Zoeteman, 2000b].

5. Conclusions

The railway restructuring in Europe leads to the creation of Infrastructure Management which faces increasing demands from transport operators and the government. Tools for enhancing the transparency and quality of design and maintenance decisions are urgently needed, but virtually unavailable. At Delft University of Technology a Life Cycle Costing approach has been developed to support railway design and maintenance processes. Key of the approach is

a decision support system (DSS) that enables an ex-ante evaluation of the (long-term) infrastructure costs and performance of different decision alternatives.
Application to the design of a Dutch high-speed railway line shows that these costs and performance are influenced by many factors. Uncertainties relate, for instance, to the expected operational conditions, the maintenance needs of innovative technologies, and the reliability of historic maintenance data. In this situation the developed DSS helps to explore the life cycle costs of different design or maintenance strategies and to test the robustness of different strategies. It should, however, be taken into account in the infrastructure performance requirements that a reliable performance forecast remains difficult in a design phase. Developing reasonable, moderate Performance Payment Regimes can avoid high risk margins demanded by private contractors, as well as high interest rates demanded by lenders.
Using the DSS for exploring life cycle costs helps in becoming sensitive to influential mechanisms in the performance of railway infrastructure. Providing information on likely life cycle costs of design and maintenance strategies proves to improve the quality and transparency of the decisions being made, although the effectiveness depends on the (active) participation of actors and the availability of technical expertise. Further development of the DSS concept could focus on the use of *uncertainty analysis*. Probabilistic distributions of outcomes can further increase the insight into life cycle costs. Another research topic is the process of data collection and validation. During the tender for the Dutch High-Speed Line the designed approach, using a standard Data Collection Checklist and Chauffeured Sessions, was not well implemented. In further research this should be better guaranteed. Involvement of the key actors in an early stage and central management support is expected to further improve the positive effects of Life Cycle Costing in design and maintenance processes.

Acknowledgement

I herewith express my gratitude to the management of the FASTRAIL Consortium, and the companies Strukton Railinfra, Alstom and Volker Stevin Rail & Traffic for the opportunity to present the research work done during the HSL South IP project.
More information on the Life Cycle Costing project, of which the case study discussed is part, can be found on http://go.to/LCC-project.

References

Bidgoli, H. DSS: principles and practice, USA, 1989

Chessa, A., R. Dekker, B. van Vliet, E. W. Steyerberg and J.D.F. Habbema Correlations in uncertainty analysis for medical decision making: an application to heart-valve replacement, Medical Decision Making 19(3) p. 276-286, 1999.

Danzer P. Methoden der LCC-Berechnung für die Fahrbahn der DB AG (Methods for Life Cycle Cost Calculation for DB Tracks), Der Eisenbahningenieur, Germany, December 2000

Dutch Ministry of Transport, Public Works and Water Management Derde Eeuw Spoor (Rail Policy in the 21st Century), The Hague, The Netherlands, 1998 (in Dutch)

Ebersohn W. and C. J. Ruppert Implementing a Railway Infrastructure Maintenance System, CORE98 Conference, Australia, 1998

Esveld C. Modern Railway Track, MRT Publications, Zaltbommel, The Netherlands, 1989

European Commission DG VII, A Strategy for Revitalising the Community's Railways, Brussels, 1997 (White Paper)

Finlay P. Introducing Decision Support Systems, NCC Blackwell Ltd., Oxford, 1994

Flanagan R. and G. Norman Life Cycle Costing for Construction, University of Reading, Reading, UK, 1983

Gerritsen R. RIB Datastromen en ECOTRACK (Information systems used at Railinfrabeheer and ECOTRACK), Railinfrabeheer, Utrecht, The Netherlands, 2001 (presentation slides, in Dutch)

Goverde, R.M.P., Bovy, P.H.L., Olsder, G.J., The Max-Plus Algebra Approach to Transportation Problems, 8th World Congress on Transport Research (WCTR), Antwerp, Belgium, 1998

Hazelaar A.H.M. *et al*. Veilig Werken aan de Infra (An Approach to Increase the Safety of Maintenance Workers), Railinfrabeheer, Utrecht, The Netherlands, 1997 (in Dutch)

Heijden, R.E.C.M. van der A Decision Support System for the Planning of Retail Facilities: Theory, Methodology and Application, Eindhoven University of Technology, Eindhoven, The Netherlands, 1986

HSL South Project Organisation Invitation to Consult, Utrecht, The Netherlands, 1999a

HSL South Project Organisation Ballastless Track for the Netherlands High-Speed Line, conference for tenderers, Utrecht, The Netherlands, 1999b

HSL South Project Organisation Invitation to Tender, Utrecht, The Netherlands, 1999c

Jovanovic S. and A. Zoeteman ECOTRACK and Life Cycle Management (LCM+): A combined approach to optimising maintenance and renewal of railway tracks and switches, Asset Management for Rail Infrastructure 2001 (International Quality & Productivity Center, IQPC Conference), London

Levi D. Optimization of Track Renewal Policy, World Congress on Railway Research, Cologne, November 2001

Moubray J. Reliability-Centred Maintenance, Butterworth-Heinemann, Oxford, UK, 1997

Ohtake T. *et al*. Practical Use of TOSMA on Track Maintenance Work, Conference on Cost Effectiveness and Safety Aspects of Railway Track, ERRI and UIC, Paris 1998

Olsthoorn A.G.M. *et al*. Life Cycle Management: Vormgeven aan de Zorg voor Beschikbaarheid (Life Cycle Management: Taking Care of Availability), Railinfrabeheer, Rotterdam, The Netherlands, 1998 (in Dutch)

Root A., J. Preston and D. van de Velde Research on Railway Competition: Great Britain, RailCo Reports, Erasmus University, Rotterdam, 1997

Rudolph R. Operational Simulation of Light Rail Systems, European Transport Conference, Cambridge, UK, 2000

Sackman H. Delphi Critique, Expert Opinion, Forecasting and Group Processes, Heath, Lexington

Stephen K.J. and A. Dell'Isola Life Cycle Costing for Design Professionals, McGraw-Hill, USA, 1995

Sugden R. and A.B. Williams, The principles of practical cost-benefit analysis, Oxford University Press, 1978

Swier, J. De Ontwikkeling van Railinframanagement in de Periode 1989-1998 (The Development of Railway Infrastructure Management in the Period 1989-1998), Railinfrabeheer, Utrecht, The Netherlands, 1998 (in Dutch)

Veit, P. Eisenbahnfahrwegstrategien auf Basis von Lebenszykluskosten, (Strategies for Track Maintenance based on Life Cycle Costs), Internationales Verkehrswesen, September 2000 (in German)

Wilson, A. (editor) Asset Maintenance Management, Alden Press, Oxford, UK, 1999

Zaalberg H. Economising Track Renewal and Maintenance with ECOTRACK, Conference on Cost Effectiveness and Safety Aspects of Railway Track, ERRI and UIC, Paris 1998

Zoeteman A. Life Cycle Costing Applied to the Management of Railway Infrastructure, Report 7-98-110-20, ISSN 0169-9288, Delft University of Technology, 1998 (in Dutch)

Zoeteman, A. Evaluating Track Structures: Life Cycle Cost Analysis as a Structured Approach, World Congress on Railway Research, Tokyo, October 1999a

Zoeteman, A. Progress Report on the Life Cycle cost Evaluation of Track Structures for HSL South, Delft University of Technology and FASTRAIL, Delft, The Netherlands, 1999b (confidential)

Zoeteman A. Bepalen waarvoor te betalen: een instrument voor de analyse van de prijs/prestatieverhouding van railinfrabeheer (Knowing What to Pay for: an Instrument for the Analysis of the Price and Performance of Railway Infrastructure), CVS Transport Conference, Amsterdam, 2000a

Zoeteman, A. Results of the Evaluation of the Provided Decision Support during the Tender of the HSL South, Delft University of Technology and FASTRAIL, Delft, The Netherlands, 2000b (confidential, in Dutch)

Zoeteman, A. Revision of the Track Renewal Policy on the Dutch Conventional Network: LCM+ Final Report, Delft University of Technology and Railinfrabeheer, Utrecht, The Netherlands, 2001 (confidential, in Dutch)