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Framework for Railway Phase-based Planning

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Abstract

In the railway field, planning the maintenance and renewal strategy from Life Cycle Cost (LCC) perspective gets more and more attentions recent years. The new approach looks at all the costs through the infrastructure life span and use the annuity (continuing payment with a fixed total annual spending) to evaluate the project alternatives. The comparison result can identify the most cost-efficient solution in a long run and therefore reduce the overall costs.

This article defines a phase-based framework to guide the railway maintenance and renewal project planning at strategic level. The framework evaluates the project options from a larger LCC scope: The costs from Train Operation Companies (TOCs) and passengers, together with the maintenance and renewal costs from Infrastructure Managers are included in the calculation.

The framework simplifies the planning processes and the LCC calculation into 7 phases. By going through the phases, the project's key evaluation indicators such as track quality and life time, the LCC annuity, Cash flow and Cumulated NPV curve over years, can be visualized into charts, so that the alternative proposals can be easily illustrated and compared.

A case study is introduced in the article to demonstrate how the framework works to compare timber sleepers and concrete sleepers from strategic planning level. Two Life Cycle Cost oriented policies are discussed to illustrate: high quality track is necessity to improve the cost efficiency of railway maintenance and renewals.

Keywords: Railway planning, Life Cycle Cost, Framework, Phase Based Planning, Decision Support System

1. Introduction

1.1. Background and Challenges

The railway is an important and sustainable mode of transport helping millions of passengers daily. Railway infrastructure maintenance and renewal (M&R) becomes a worldwide challenge^[1]. An increasing

performance is required by government and Train Operation Companies (TOCs), such as more trains per hour, longer operating hours and better punctuality. On the other hand, it conflicts with the increasing budget pressures and operational restrictions ^[2]. Infrastructure Manger (IM) has always to find a way to improve the project cost efficiency.

As a response IM has started to look at all the costs through the infrastructure life span and use Life Cycle Cost (LCC) principle to evaluate the railway maintenance and renewal projects ^[3]. This approach can help to identify the most cost-efficient solution in a long run and therefore reduce overall costs ^[4].

However, how to estimate LCC is a complex and time consuming task. It involves many factors such as track degradation rate, infrastructure life time, potential train delays due to track quality etc. A heavy data collection and analysis are needed to make the estimation. It requires a toolkit to simplify the planning processes, convert the factors into monetary values and estimate the proposals' costs from LCC perspective.

1.2. Motivation and Objectives

An early analysis of Rail Net Denmark (*Banedanmark*) states that the average age of the rail track in Denmark is too high, with a current average age of 24 years compared to the recommended 20 years ^[5]. It means that a big amount of the track renewal and maintenance work has been planned or will be planned in the coming years. In practice, IMs are going to make many similar planning decisions. A transparent planning tool with the previous data and experiences can contribute to the later project planning.

The objective is to develop a so-called "Railway phase-based planning framework" to help decision-maker, from the Life Cycle Cost (LCC) perspective, to plan the railway infrastructure project more economically.

2. Life Cycle Cost Assessment

2.1. Life Cycle Cost

Life Cycle Cost (LCC) is a main principle of economic investment evaluation. It counts all costs from one investment until the next re-investment. LCC is more and more popular to evaluate the railway infrastructure project ^[6]. The LCC annuity, continuing payment with a fixed total annual spending (table 2), has been calculated through life span to assess the infrastructure project alternatives. In the recent years, the main LCC approach in the railways is to extend infrastructure life time through a better maintenance strategy. So the slightly-increased total spends with a longer life span can result in a better yearly expense. The new track maintenance strategy in Netherlands, as a good example, shows that it can lead to at least 10% reduction of forecasted budget ^[2].

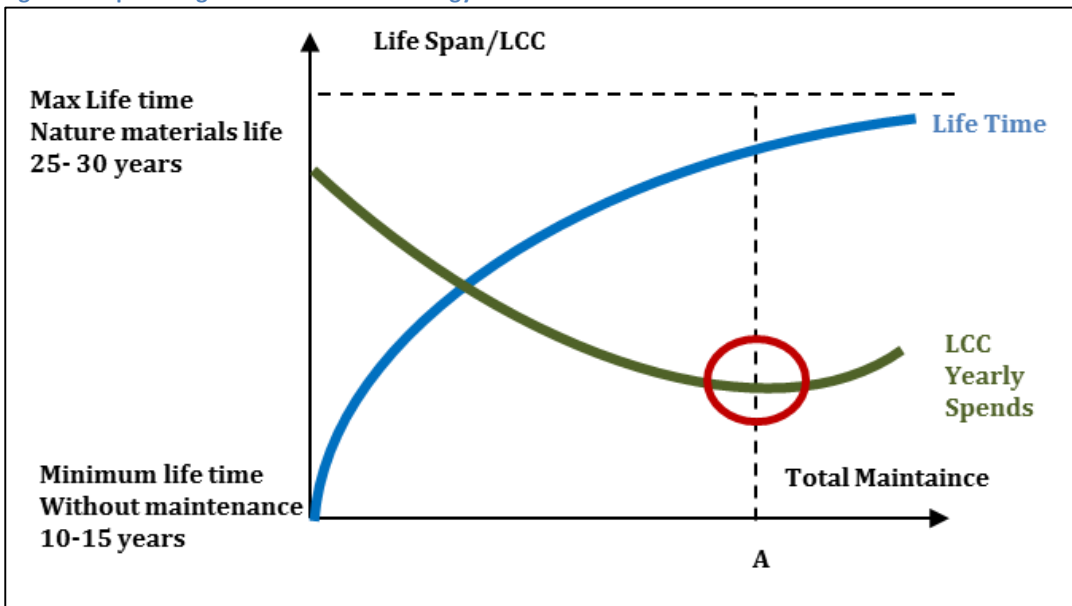
2.2. The Limitations of the Existing Approach

LCC concept is under developing in railway field. The most of the focuses are still limited to the direct-costs, so-called 'planned costs', such as construction, maintenance, renewal costs and disposal values. It leads to an under-estimation without counting the 'non-documented costs' or 'un-planned costs' such as train delays, emergent track reparations caused by poor track quality which are definitely costs, but the exact value is either uncertain or not transparent during the planning. As a consequence, reducing maintenance was widely accepted in 1990s. Many governments, for the short term saving, cut the maintenance budget drastically. It caused punctuality problem of the railway system ^[7] a couple of years later. In the long run, the later costs, for instance track reparation and clearing the delayed traffic, were unfortunately more expensive than the early savings. Therefore, it is important to extend the LCC, including 'non-documented costs' or 'non-planned cost' by using appropriate procedures to measure uncertainty, when plan the railway long term M&R strategy ^[8].

Additional, other optimization today is dealing with the trade-off between renewal and maintenance. It is based on the analysis that the LCC yearly spends curve shown in the following Figure 1. The infrastructure

life time can be prolonged through increasing maintenance. But it can't be infinitely extended due to nature materials life. So there exists a LCC minimum yearly spends Point A.

Figure 1 - Optimizing the Maintenance Strategy

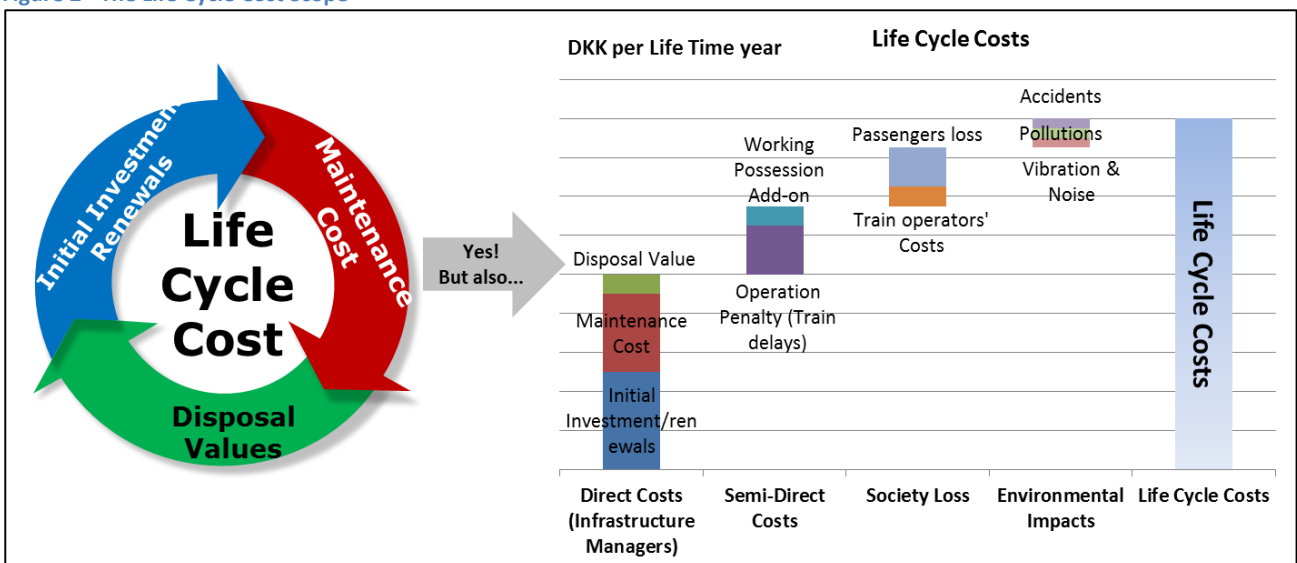


However, when the focus is still on IMs, it is again risky to under-estimate the overall costs. The maintenance itself takes away the line availability. The closure of railway lines by the maintenance purpose also takes away the track availability and brings loss for passengers and TOCs, especially at the heaviest railway sections like central station. The cost of a simple tamping maintenance for example is no longer 150 DKK per track-meter^[9], but much more than that. The increasing maintenance will not result in the decreased LCC yearly spends in such case. Therefore the basis of the optimization is not suitable any more. Instead the larger scope of LCC including the preferences from IMs, TOCs and Passengers are needed.

2.3. A Broader Life Cycle Cost Scope

This is an important new progress in this paper to acknowledge a broader LCC scope, including the non-documented semi direct and indirect costs. The extended LCC is illustrated as following Figure 2,

Figure 2 - The Life Cycle Cost Scope



Direct Costs: It includes the IMs' costs like renewal costs, maintenance costs and disposal values. Disposal values could be either positive (for reuse purpose) or negative (waste disposal). Direct costs can be planned in advance and the unit price is more or less fixed.

Semi-Direct Costs: Working possession costs and operation penalty are defined as semi-direct costs. The unit price of this cost-type is not fixed but different from project to project. It depends on many pre-conditions, for example working possession costs depends on the possessions time, work type and working shifts. The same amount of track maintenance can cost quite differently among working at nights, in weekends or on daytime. The costs can only be calculated after the detailed working plan was finalized; Operation penalty is the virtual costs related to the track quality. It includes the costs of un-planned track reparation and train delays loss. Many conditions such as the drainage system, alignments, traffic loads, weather etc. can impact the calculation.

Society Loss: The new framework suggests include the passenger loss and train operations' costs during project planning. When the track quality is under threshold, the rolling stock speed is normally restricted to secure the railway safety. In such case, passengers spend more travel time. TOCs have to sign more trains into service. The society loss could be the key factor to impact the track maintenance and renewal strategy, especially for the most intensive railway sections.

Environmental Impacts: It is the cost-type imported from road construction planning field. The infrastructure maintenance strategy can also impact the environment by CO2 pollutions, vibration & noise and accidents. It can be looked as the additional penalty to the M&R alternative plan in which the track tamping and grinding are not enough.

Capital Costs: Railway infrastructure can last long time so the railway M&R planning is similar to the long term investment financially. It is necessary to include the capital costs for all the above 4 cost-types. The LCC yearly spends should then be replaced by the LCC annuity (ANN) which is shown in the following table.

Table 1 - Annuity Formulas

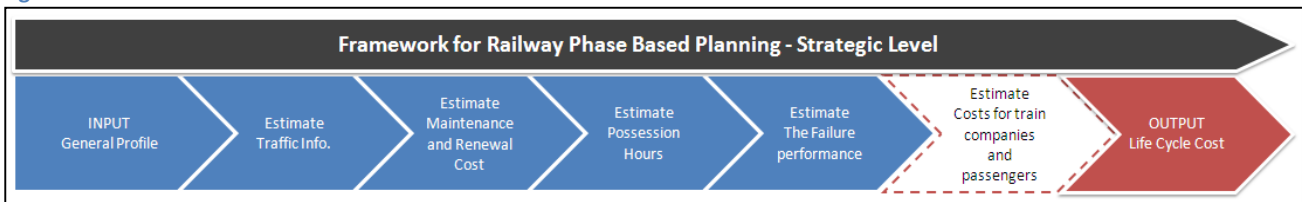
Formula	Definition and Explanation
$NPV = \sum_a \sum_{y=0}^n \frac{C_{y,a}}{(1+i)^y}$	<p>The Net Present Value <i>NPV</i> is the sum of the discounted Life Cycle costs <i>C</i> during all years (<i>y</i>) and for all activities (<i>a</i>). Year <i>n</i> is the last year, The interest rate (<i>i</i>) applied.</p>
$ANN = \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \cdot NPV$	<p>Annuity <i>ANN</i> is any continuing payment with a fixed total annual amount. It is calculated in multiplying the net present value with the capitalizing factor (<i>CF</i>)</p> $CF = \frac{(1+i)^n \cdot i}{(1+i)^n - 1}$

3. The Framework For Railway Phase-Based Planning

Life Cycle Cost estimation is complex because any small change to the M&R plan can impact the final LCC annuity. For instance, if the track tamping interval is extended from 2 years to 3 years, all the 4 cost types and the infrastructure life time will change (Direct cost and life time decreases; semi-fixed cost and society cost increases). It could result in an either better or worse LCC annuity. In the other words, any small improvement in planning could result in a better LCC. The phased-based planning framework is therefore developed to help IMs to find out a cost efficient strategy.

The tracks and switches account for about 60% of the total maintenance and 80% of the renewal expenses ^[10], The Framework is mainly to plan the strategic (+5 years) track system maintenance and renewal work. The Life Cycle Cost estimation is defined into the following phases.

Figure 3 - Framework Phases



3.1. Phase 1: Input General Profiles

Phase 1 is the starting step where the line profiles are documented. Such as,

- Length of the line
- Max axel load
- Number of track sections
- Number of Switches and Crossings (S&C)
- Rolling Stock speed range
- Sub-structure condition
- Ballast, sleepers, rails, fastening type etc.

Some of above data are used to calculate the traffic loads, track quality, life time in the following phases. The other information is for documentation purpose. Generally, it provides the project overview.

The many estimates described below are typical non-documented and rather uncertain by nature. This calls for subjective expert evaluations. However such evaluations are subject to serious pitfalls, for example wishful thinking, over optimism, lack of knowledge, etc. The type of analysis in this paper is exposed triple or more, because 1) two alternatives are compared, 2) benefits and costs are divided, 3) because of the rather long time horizon, and 4) the result is exposed to future political decisions. It is advocated to use scientifically based and accurate evaluation procedures which has documented to cope with such pitfalls [14][15][16].

3.2. Phase 2: Estimating Traffic

This phase is used to estimate the average load on the infrastructure. The gross tons per year can be calculated in the traffic profile table which includes,

- Number of passenger trains per day
- Number of freight trains per day
- Weekend traffic rate
- Traffic increase rate per year
- Rolling stock conditions
- Operation hours
- Average passengers per train etc.

Some data requires the coordination from TOCs, such as average passenger per train, rolling stock condition etc. It therefore involves the TOCs at early planning stage.

The rolling stocking condition is included because the bad wheel condition can increase the rail wear rate. It indirectly increases the maintenance requirement. It's better to know it in advance before drafting the maintenance plan. The passenger-kilometer per day is also calculated to indicate the passenger loss during the maintenance. It is another important factor that can impact the maintenance scheduling decision.

3.3. Phase 3: Planning Maintenance and Renewal

Phase 3 consists of an estimation of the periodic maintenance (major works, such as rail grinding and track tamping, with intervals of more than a year) and partially renewals. The M&R direct costs and interest rate are collected in this phase. When the track life span was estimated, the LCC annuity and down payments such as the depreciation of track value can be calculated.

To estimate the life time and track quality changes over years, the track behavior equation is quoted. Experience shows track quality degradation is a function of time and load on the track. In close cooperation with the Austrian Federal Railways (ÖBB), the University of Technology, Graz, set up a data warehouse and derive the track behavior Equation ^[6].

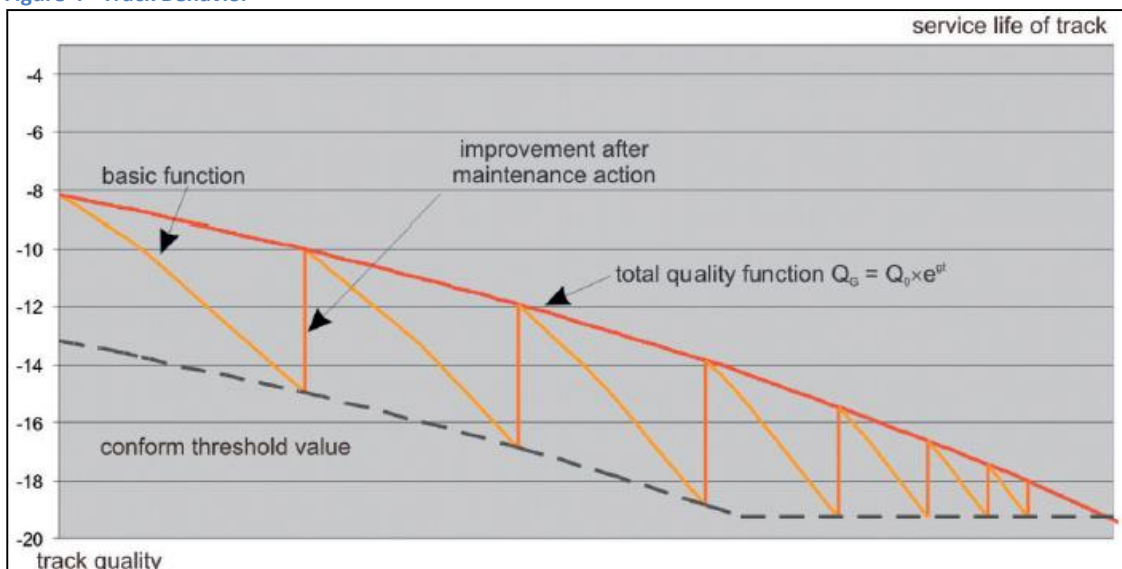
$$Q = Q_0 * e^{-b*t}$$

Where,

- Q_0 denotes the initial track quality and b is the rate of deterioration over time t .

Maintenance can increase the track quality and extend the track life time, but never result as a 'new track'. At end of the track life time, the track quality decreases fast. To protect the track quality from crossing the threshold value, it requires more frequently maintenance as illustrated in the following figure.

Figure 4 - Track Behavior



In this phase, initial track quality and threshold is estimated, track behavior functions can be built to simulate track life time. Expert experiences are highly recommended afterwards to adjust the simulation result. Because simulation could be dangerous ("rubbish in, rubbish out!"). Experience shows that allowing experts evaluate the issues, while using a relevant procedure yields often better results, than simulation, where it is difficult to control the entire procedure ^[16]. Switches and Crossings are one of the main components that impacts the maintenance cost. It is recommended to include them as well. As output, the yearly depreciation of track value and maintenance annuity is calculated from this phase.

3.4. Phase 4: Possession Time Estimating

Based on the maintenance and renewal estimation from Phase 3, the total net possession shift can be estimated in Phase 4. The working time should be round up to working shift hours. The railway project normally plans in this way in the practice. For example, a 3 hours night work actually costs as 7 hours night work shift. The short working time easily results in a higher price for the maintenance.

The possession time estimating is based on the assumption of M&R working speed. Thus it is crucial to collect the detailed practical data. As results, the total possession time in calendar days, working hours are calculated; the M&R annuities are adjusted in this phase.

3.5. Phase 5: Estimating the Failure Penalty

Phase 5 is to estimate the delay penalty based on the track Reliability, Availability, Maintainability and Safety (RAMS) as defined in the following table ^[11]. The delay penalty is estimated through the infrastructure failure and train delay simulation.

Table 2 - RAMS Definitions

RAMS	Brief
Reliability	Reliability can be calculated by using the predict failure approach. The failure probability indicates the reliability %.
Availability	Availability is indicated by the ranking of the total planned possession time per year in the reversed order.
Maintainability	Maintainability is to indicate how fast the track can be repaired.
Safety	Safety has many definitions. Here the track threshold value indicates the Safety level.

The main assumptions, such as average delay minutes per train, average cancellation, number of delay trains per failure, Mean time between failures and Penalty rate under threshold, have to be made in the phase. The same as in Phase 3, S&C is also important to include into the calculation in Phase 5.

3.6. Phase 6: Estimating the costs for Train Operators and Passengers

Passenger Loss: The way to calculate passenger loss is based on Value of Time (VoT) for delays. The train cancellation can be looked as a much delayed train. The framework suggests the following formula to calculate the potential loss for passengers.

$$Passenger\ Loss = Cumulative\ Delay\ Hours * Number\ of\ passengers * VoT$$

However different type of passenger has different time values. There are many statistics showing VoT in Denmark for public transport ^[12]. The assumption of the average railway passenger VoT has to be made according to the time period and passenger types.

Table 3 - Value of Time for public transports

Value of Time	Unit	2008	2009	2010	2011	2012	2013	2014
Unit Value of Time - Public Transport								
<i>Travel Time</i>								
Household	kr./hour pr. person	80	76	77	78	80	81	83
Employee	kr./hour pr. person	338	322	325	329	335	342	350
Others	kr./hour pr. person	80	76	77	78	80	81	83

TOCs' costs: Additional costs generated at the TOCs' side due to the railway M&R operation, such as the administration costs to plan the alternative routes, renting train-buses and announcing the changes. It also includes the potential TOCs' loss like the revenue loss due to reduction of number of passengers in both long term and short term, putting additional trains into service when the rolling stock speed is restricted, additional rolling stock maintenance due to bad track quality and so on. Meanwhile these various costs are likely to be biased through wishful thinking, tactical reasons, or one of the many pitfalls while evaluating most uncertain values ^[16]. It needs a further investigation and systematic approaches to estimate them with train operators.

3.7. Phase 7: Output the Overview of the Life Cycle Cost Annuity

After going through all the previous phases, Phase 7 reaches the 4 main outputs to give the overview,

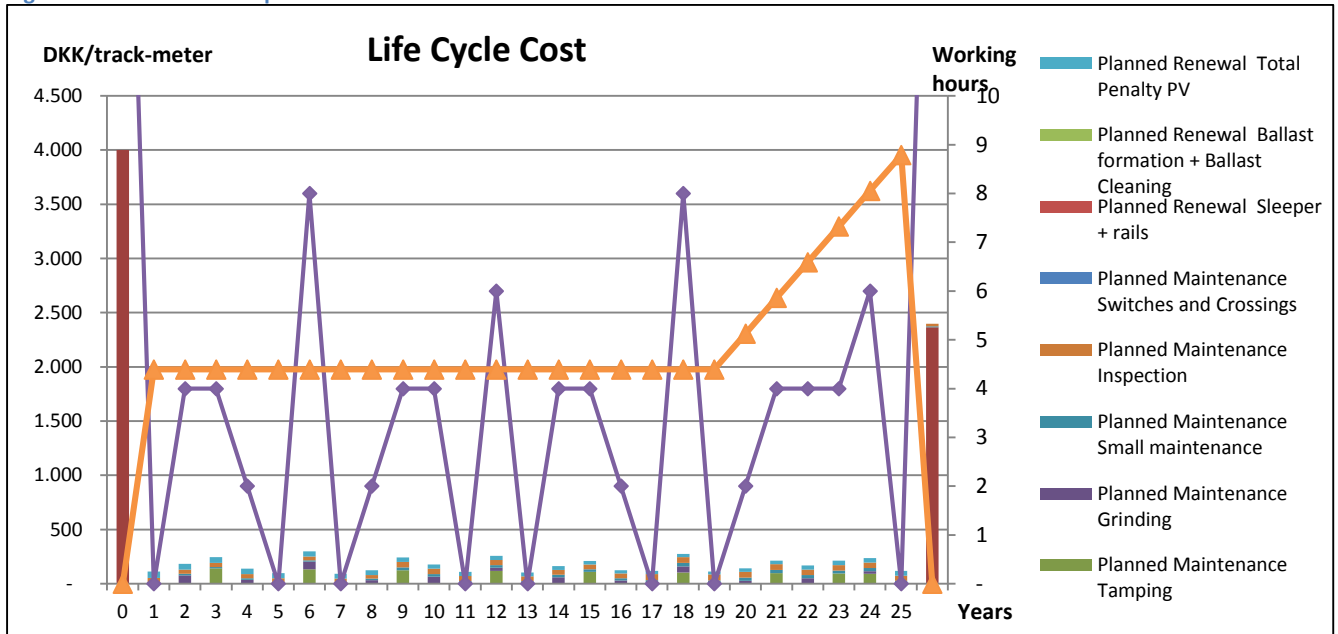
- Track Behavior chart (Figure 6)
- LCC Annuity chart (Figure 7)
- Cash Flow curves (Figure 5)
- Cumulated NPV chart (Figure 8)

Track Behavior Chart is to show the track quality over years and maintenance actions.

LCC Annuity Chart is the chart where all alternatives can compare to each other. It includes the initial investment depreciation, the maintenance and renewal LCC annuity, the potential penalty caused by the potential infrastructure failure and the total amount of net possession time per year.

Cash Flow curves illustrates the cash flow in life span. Besides the cost information, the possession time per year is also included in the chart to give reference.

Figure 5 - Cash Flow Example



Cumulated NPV chart is to show the cumulated value of investment through years. It mainly used to compare similar alternative solutions.

4. Case Studies

4.1. Concrete sleeper vs. Timber sleeper



Due to the greater weight which helps to remain in the correct position longer, concrete sleepers have some advantages such as, a longer service life and less maintenance; the concrete fastenings were cheaper and easier to obtain than timber and better able to carry higher axle-weights and sustain higher speeds.

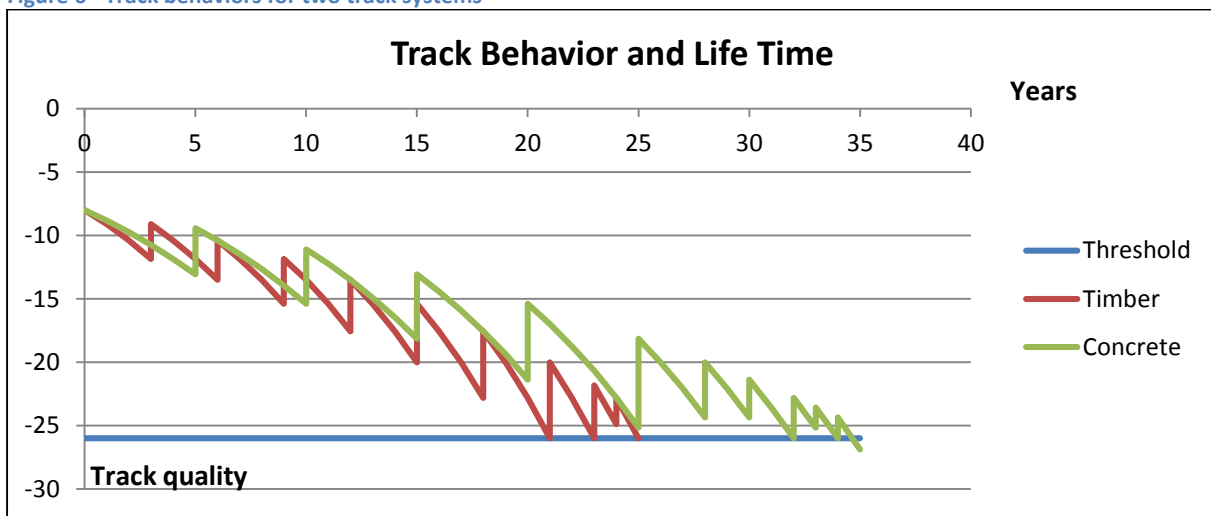
While concrete sleepers are more expensive and also have other disadvantages: when trains derail and the wheels hit the sleepers, timber sleepers tend to absorb the forces and could be reuse, while concrete sleepers have to be replaced; concrete sleepers are heavier and it requires heavy logistics transport. To compare two types of sleepers from LCC, the assumptions are made in the following table,

Table 4 - Main assumptions

Items	Concrete	Timber
Service Life (years)	35	25
Price (DKK per track-meter)	4.500	4.000
Tamping every	5 years	3 years
Reaching threshold years without maintenance	12	9

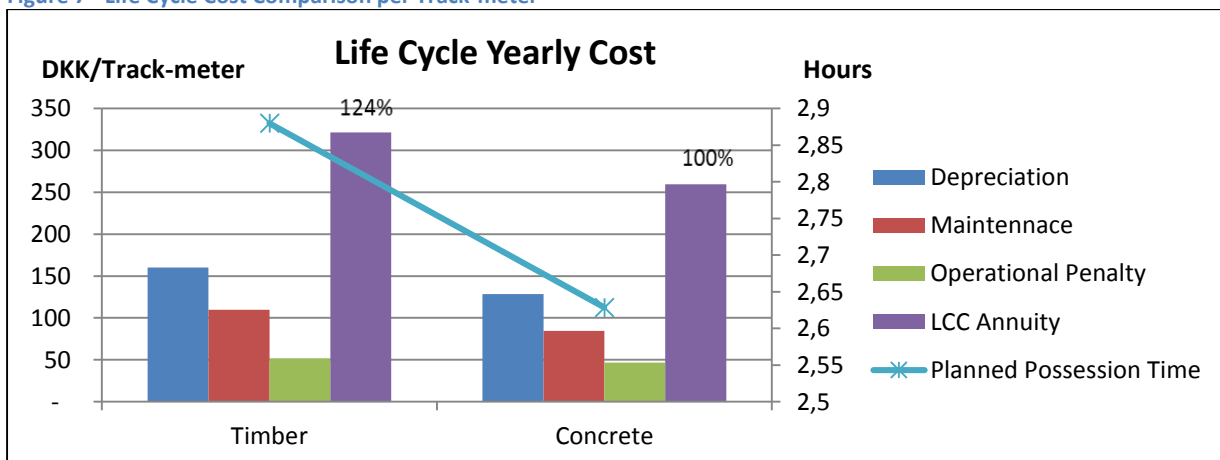
By using the phase-based planning framework, the life time can be simulated for two solutions. Green curve states the concrete sleepers and the red curve shows the timber sleepers ^[13].

Figure 6 - Track behaviors for two track systems



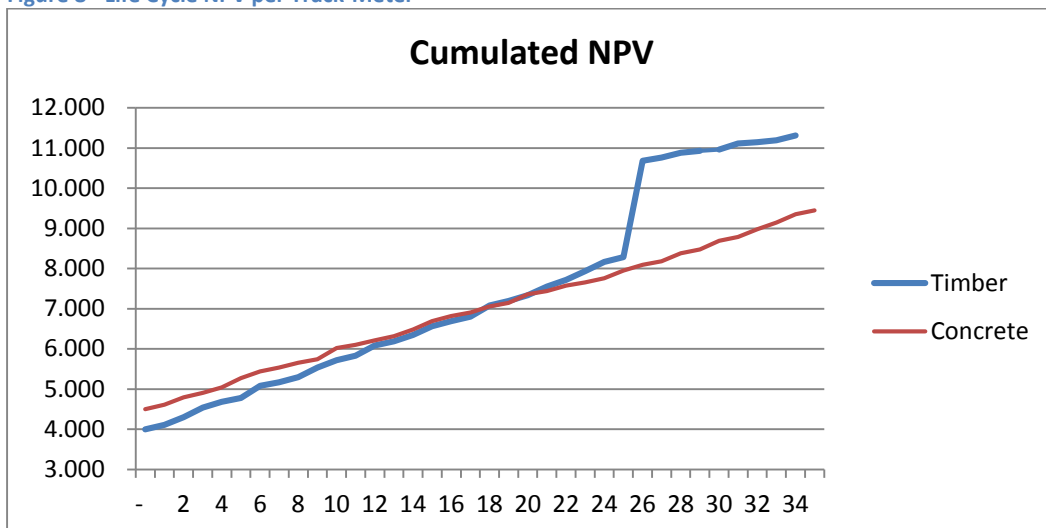
The initial track quality of timber sleeper has been set the same as, namely the concrete one for comparative analysis purpose. The interest rate is a sensible value. Many interested parties prefer different values due to scarce investment capital. A 'political bias' is often be present here ^[16]. In this case, the interest rate is set to 2%. The LCC annuity is calculated based on this value. It is highly recommended to do sensitivity analysis afterwards.

Figure 7 - Life Cycle Cost Comparison per Track-meter



Concrete sleeper is a worthy investment from LCC perspective. Timber sleeper would be 24% more expensive than concrete sleeper. The cumulated NPV curves can be seen as following,

Figure 8 - Life Cycle NPV per Track-Meter



Concrete sleeper is more expensive to construct. But it requires less maintenance work and has longer life span. Timber sleeper solution is cheaper at construction but becomes more expensive after 20 years due to its higher maintenance costs and it becomes even more expensive after renewal at the end of its life span 25 years.

4.2. LCC Oriented Policy discussion

High quality track + less maintenance vs. Low quality track + more often maintenance

Let's compare the following two policies,

- High quality Track: Install high quality track with maintenance every 5 years
- Low quality Track: Install low quality track but maintain it every 3 years

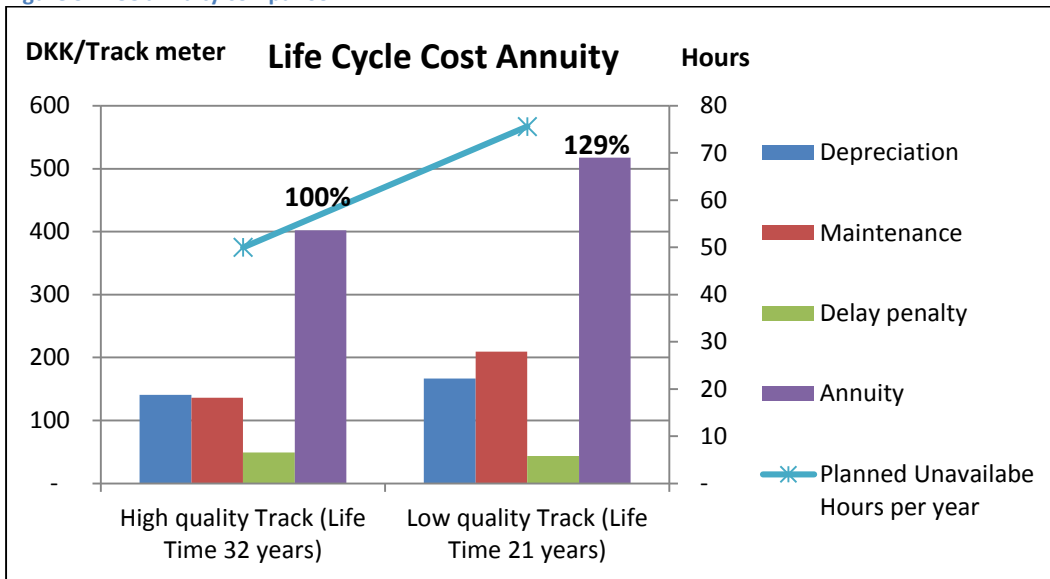
Based on the following assumptions, and the outputs from the framework, it concludes that even the low quality track alternative have higher frequency of maintenance, it still ends up with the shorter service life. It is more expensive (129%) to build and maintenance the low quality track.

Table 5 - Main Assumptions

Interest Rate	2%	
Gross Maintenance cost	900	DKK/meter
Average delay minutes per train	5	minutes
Average Cancellation factor	20	minutes
DKK per delayed train-hour	10,000	DKK
DKK Per cancelled train-hour	30,000	DKK
Line Length	5,000	meter
Double Track	yes	

Initial Quality	Low	High
Initial Investment (DKK/T-meter)	3,500	4,500
Maintenance - amount of tamping in life time (times)	6	7
Delay penalty (DKK/T-meter)	43	49
Life Time	21	32
Annuity	518	402

Figure 9 - LCC annuity comparison



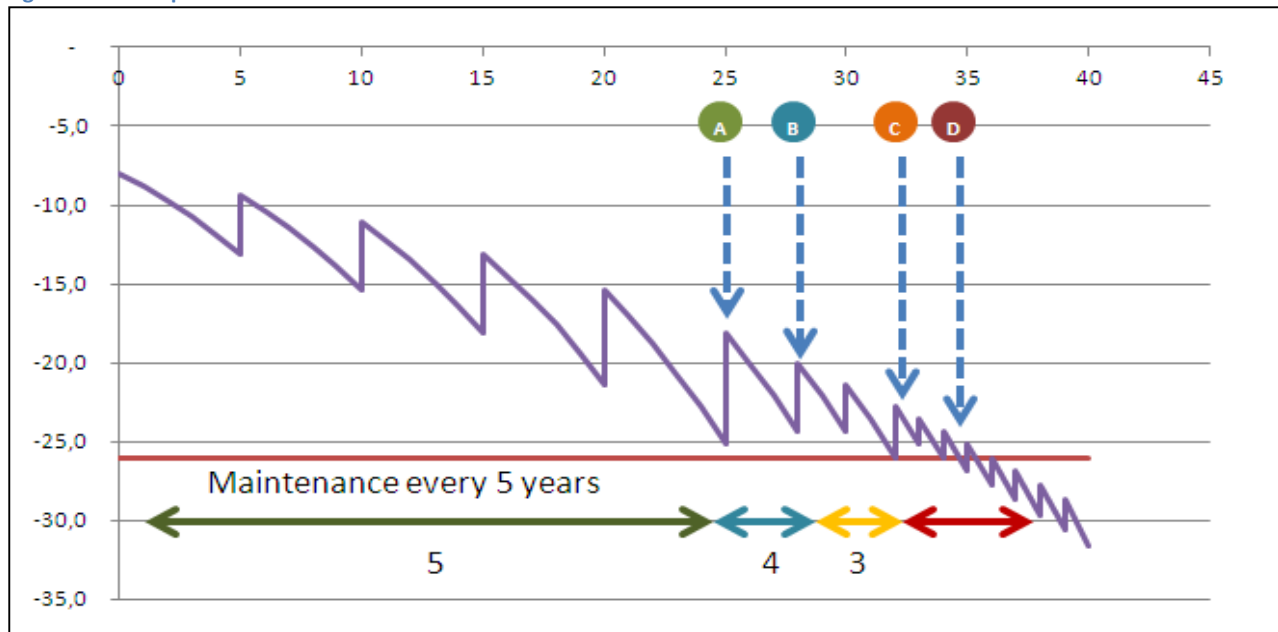
This conclusion leads to a high quality track strategy. Installing high initial quality with reduced maintenance costs is much more efficient. High quality track is not only technically essential but also economically necessary from LCC perspective.

Positive track renew vs. Maintenance

Track maintenance improves the quality but it can never reach the new track quality. The following figure shows the track behavior under 5 years' maintenance interval. When approaching the threshold value, minimum safety requirement force IM to maintain the track more often.

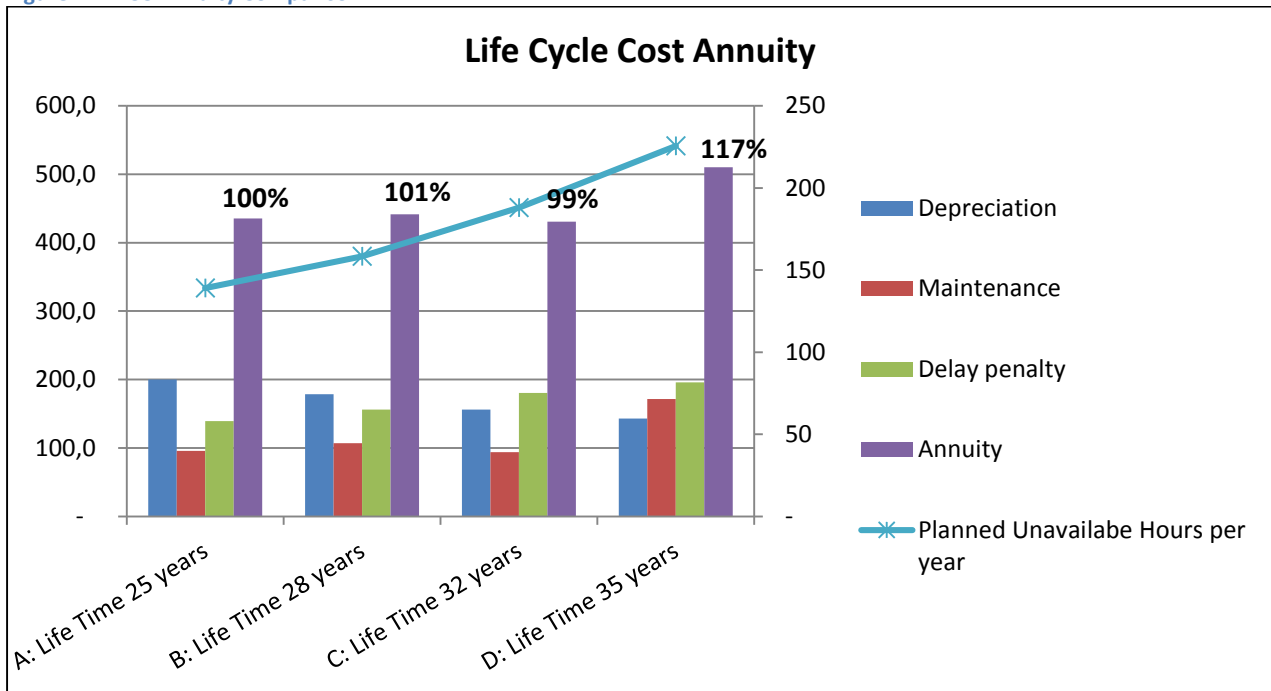
To answer the question: When should the track system be totally renewed? 4 time points (A-D) are selected in the following figure.

Figure 10 - Time points to renew the track



From the LCC annuity comparison, it concludes that it is not the best that re-installing the track system too often. Maintaining the track until to the time point where yearly maintenance is required is the most economical solution in this case.

Figure 11 - LCC Annuity Comparison



5. Conclusion

Maintaining and renewing rail infrastructure (M&R) becomes a worldwide challenge. An increasing performance is required by government and train operators, such as more trains per hour, longer operating hours and better punctuality. On the other hand, it conflicts with the increasing budget pressures and operational restrictions. A decision support toolkit is required to help Infrastructure Managers to improve the project cost efficiency. Additionally, planning railway infrastructure projects, Infrastructure Managers have to make many similar decisions, such as choosing the infrastructure component; deciding the maintenance intervals; and scheduling renewals. A general planning framework for enhancing the transparency, best practice sharing and documentation is needed.

A phase-base planning framework is therefore developed to support railway decision making at the strategic level. It integrates the Life Cycle Cost approach and simplifies the planning processes into 7 phases. It can help Infrastructure Managers to evaluate alternative proposals and identify the most cost-efficient solutions from the LCC perspective. However evaluation pitfalls are especially damaging for a relevant result in these analyses. It is due to the LCC principle and the long time frame. This calls for the use of evaluation procedures which are able to cope with these pitfalls ^{[14][15][16]}.

A case study is introduced in the article to demonstrate how the framework works to compare timber sleeper and concrete sleepers from strategic planning level. Two Life Cycle Cost oriented policies are also discussed to illustrate: the high quality track is not only technically essential but also economically necessary to improve the cost efficiency.

List of Abbreviations

IM	Infrastructure Manger
LCC	Life Cycle Cost
M&R	Maintenance and renewal
NPV	Net Present Value
RAMS	Reliability, Availability, Maintainability and Safety
S&C	Switches and Crossings
TOCs	Train Operation Companies
VoT	Value of Time

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