



Project no. TIP5-CT-2006-031415

## INNOTRACK

Integrated Project (IP)

Thematic Priority 6: Sustainable Development, Global Change and Ecosystems

### D6.2.4 - Database and requirements (as input for WP6.5)

Due date of deliverable: 2008/10/30

Actual submission date: 2009/01/28

Start date of project: 1<sup>st</sup> September 2006

Duration: 36 months

Organisation name of lead contractor for this deliverable:

ADIF

Revision Final

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

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## Glossary

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<b>Abbreviation / acronym</b>	<b>Description</b>
CBS	Cost Breakdown Structure
IM	Infrastructure Life Cycle Cost Manager
LCC	Life Cycle Cost Analysis
LCCA	Mean Time Between Failure
MTBF	Mean Time To Repair
MTTR	Net Present Value
NPV	Product Breakdown Structure
PBS	Reliability, Availability, Maintainability and Safety
RAMS	Work Breakdown Structure

# 1. Executive Summary

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INNOTRACK addresses mainly the objective of reducing Life Cycle Costs (LCC), while improving the RAMS characteristics of a conventional line with a mixed traffic duty. In the field of railways, RAMS technology and LCC are starting to be implemented and will provide a definite advantage to the IM:s (Infrastructure Manager) in helping calculate costs for the implementation of innovative technologies. In the frame of INNOTRACK these methods will be defined at a European level and used to identify cost drivers and assess the track components. The sub-project SP6 deals with RAMS and LCC. Work Package 6.2 deals with Life Cycle Cost Methodology and this last deliverable presents guidelines on the requirements to address LCC analysis within Work Package 6.5.

## 2. Introduction

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The Project INNOTRACK aims to develop a cost-effective high performance track infrastructure for heavy rail systems. INNOTRACK addresses mainly the objective of reducing Life Cycle Costs (LCC) while improving the RAMS characteristics of a conventional line with a mixed traffic duty through innovative solutions.

INNOTRACK project brings IM (infrastructure managers) and railway supply industry together, to investigate and evaluate leading edge track system technologies, adopting a controlled methodology to assess life cycle cost benefits of “track-technology solutions” and of a set of emerging railway hardware and software solutions. It will also support the overall sustainability of the railway sector, meeting needs such as the increase of track availability and network capacity. The results of this project will be assessed based on a standardised LCC formulation developed within the project, based on best LCC practices at EU level.

Optimisation of track constructions or track components regarding technical and economic requirements is essential for railway companies to fit the market and to compete against other means of transport. Due to the long lifetime of the track and track components – ranging between 20 to 60 years – pre installation technical and economic assessments are necessary to optimize the track construction and get the return on investment (ROI) in a manageable timeframe. LCC and RAMS technologies are two acknowledged methods for assisting the optimisation process.

LCC is an appropriate method to identify cost drivers and to gather the costs of a system, module or component over its whole lifetime including development, investment maintenance and recycling costs. Different views and evaluations allow the comparison of different systems and deliver necessary information for technical and economic decision.

In the field of railways, LCC methods are starting to be implemented and will provide a definite advantage to the IMs in helping calculate costs for the implementation of innovative technologies. In the frame of INNOTRACK these methods will be defined at a European level and used to identify cost drivers and assess the track components. The INNOTRACK project is divided in 7 Sub-projects:

1. Duty
2. Track support structure
3. Switches and crossings
4. Rails and welds
5. Logserv
6. LCC and RAMS
7. Dissemination and Training

This report is included in Sub-project 6 LCC and addresses guidelines on the requirements for LCC modelling of INNOTRACK innovations within WP6.5.

### 2.1 Objective

The purpose of this deliverable is to define the database requirements for INNOTRACK LCC modelling (to be performed within WP6.5).

More specifically, the objectives are:

- To expose guidelines on LCC cost matrix and information requirements as input to WP6.5
- To establish the structure and format of the cost database (based on the software to be used)

## 2.1.1 Activities

- Preparation of a questionnaire for the definition of reference and optimized systems (innovations) within each SP's (with WP6.5)
- Definition of key issues concerning:
  - Building of LCC models
  - The reference costs database
  - Cost harmonisation procedure
  - LCC Calculation and sensitivity analysis

## 2.1.2 Time schedule

The time to furnish the report (D6.2.4) was 18 months from the start of the project. The status of the report will be “public”.

## 2.2 Organisation and resources

Organisation and resources for this work package are given in Table 1. ADIF is responsible for deliveries of WP 6.2 which includes the current deliverable D6.2.4.

Workpackage	6.2 – Life Cycle Cost Methodology			Start date or starting event:			M1
Participant id	UIC	VAS	BV	ADIF	Alstom	NR	OBB
Person-months per participant	2.0	3.0	3.0	5.5	1.0	2.0	3.0
Participant id	DB	Corus					
Person-months per participant	6.0	1.0					

**Table 1 – organisation and resources**

Another partner in the working group is ProRail.

## 2.3 Information acquisition

Information on LCC was obtained from the following sources:

- Previous Deliverables
- Published papers, project reports and thesis
- DB LCC templates
- Data provided by UIC on some results of LICB project

### 3. Database and requirements

#### 3.1 Requirements for Life Cycle Cost assessment of INNTRACK innovations

As presented in D.6.2.1, life cycle cost analysis (LCCA) is a structured method to assess all costs incurred within a given system along the technical life cycle considered for this system. Major phases of the system life cycle must be included in the analysis (i.e. concept and definition, design and development, manufacturing, installation, operation and maintenance and disposal phases). LCC models consists of a 3 dimensional matrix that includes a breakdown of the product to lower indenture levels (PBS), a cost categorisation of applicable resources such as labour, materials, equipment, etc. (CBS) and a time axis or life cycle phases where each work or activity performed is allocated to each cost element (Figure 1).

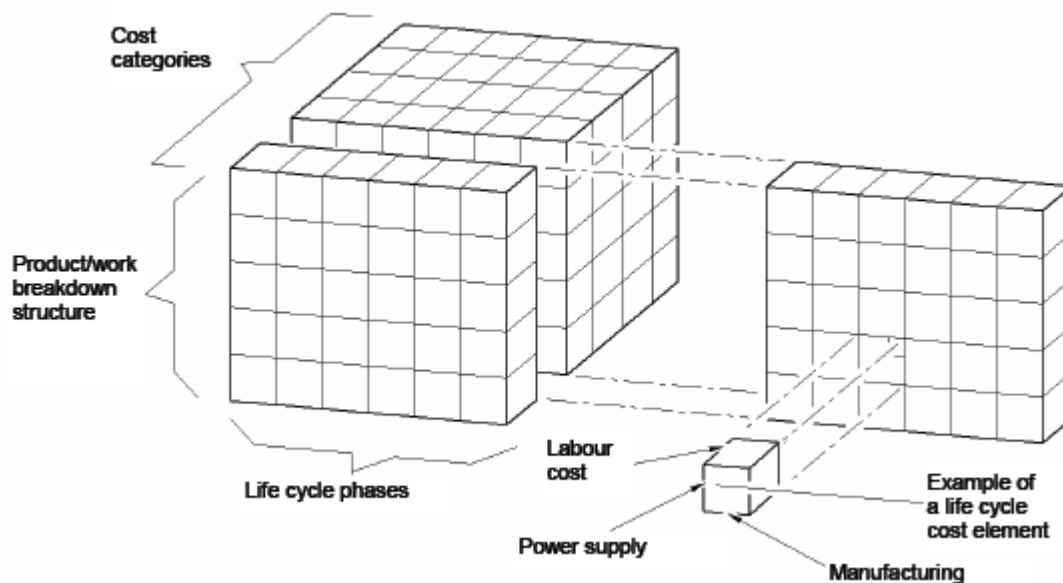


Figure 1 - Cost element concept

When applied to railway track LCC analysis, the cost matrix can be summarized as the example of Figure 2.

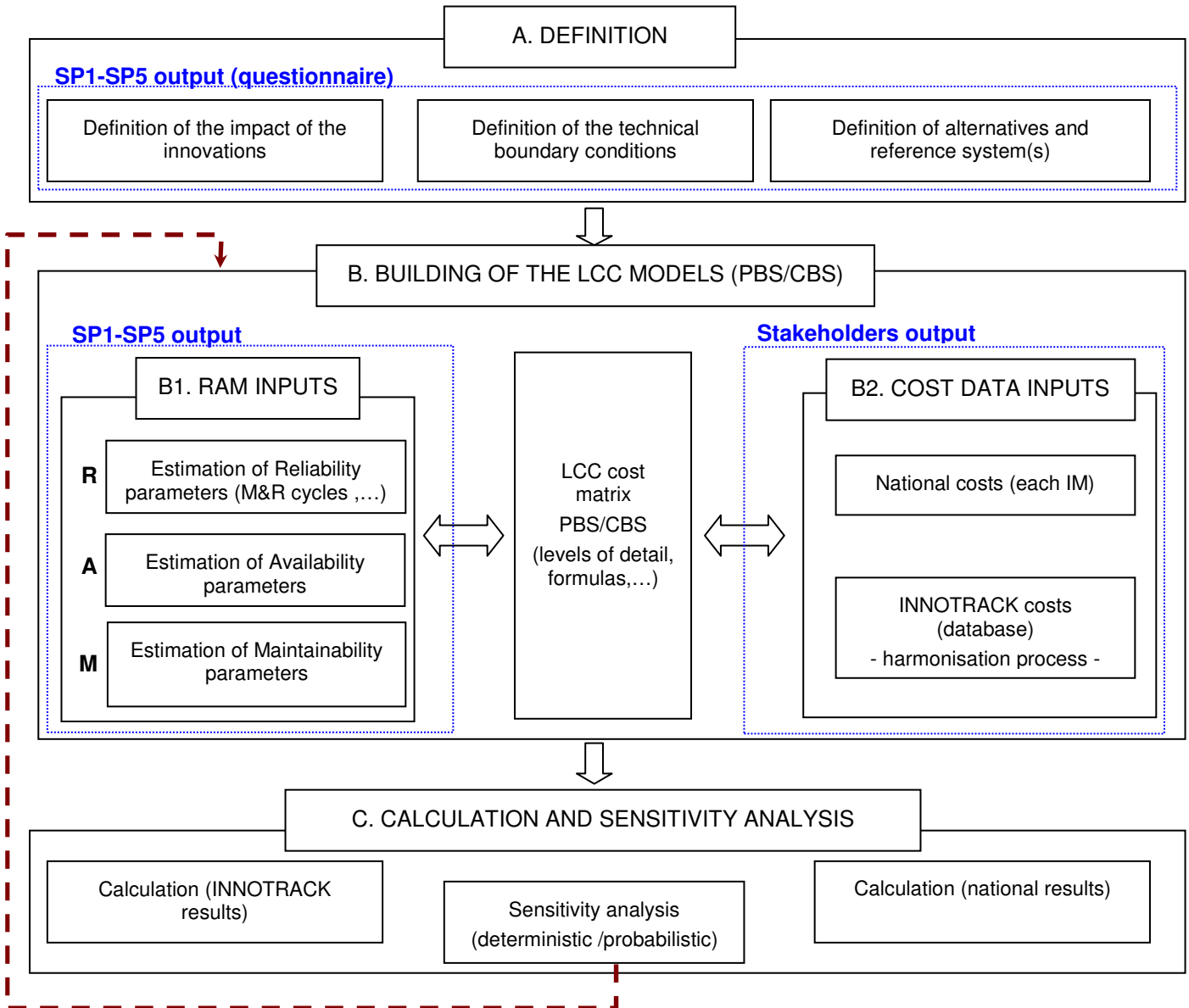
I. Procurement	II. Operation	III. Maintenance	IV. Non Availability
I.1 Preparation one-time / generic/ product-specific (product family) I.2 Preparation recurrent / project-specific (single product) I.3 Investment I.4 Imputed residual value I.5 Decommissioning / retraction / sale / removal (tasks) I.6 Disposal / recycling (material) I.7 Others	II.1 Service II.1.1 Personal costs II.1.2 Energy II.1.3 Cleaning II.1.5 Provision II.1.6 Insurance II.1.7 Fees II.1.8 Communication II.1.9 Other costs	III.1 Preparation one-time III.2 Inspection/ Diagnostic III.3 Service III.4 Maintenance preventive (condition based/ pre-determined) III.5 Mtn. corrective (Deferred/ immediate) III.6 Residual value III.7 Disposal/ Recycling (material) III.8 Design and system support III.9 Others	IV.1 Planned IV.1.1 Malfunctions IV.1.2 Delays IV.1.3 Less Serviceability IV.2 Unplanned IV.2.1 Malfunctions IV.2.2 Delays IV.2.3 Less Serviceability

Figure 2 - Example of DGAG short version of LCC cost matrix for railway track analysis



The capital budgeting techniques and the requirements for the discounting factors and the time horizon to be used were discussed within D6.2.1. This report will address the input data requirement to perform LCC analysis of INNTRACK innovations.

In a general way, the LCC assessments to be performed within the project should follow a flow chart similar to the one presented in Figure 3.



**Figure 3 - Simplified LCC analysis (to be performed within WP6.5) flow chart**

### 3.2 Step A- Definition of INNTRACK innovations

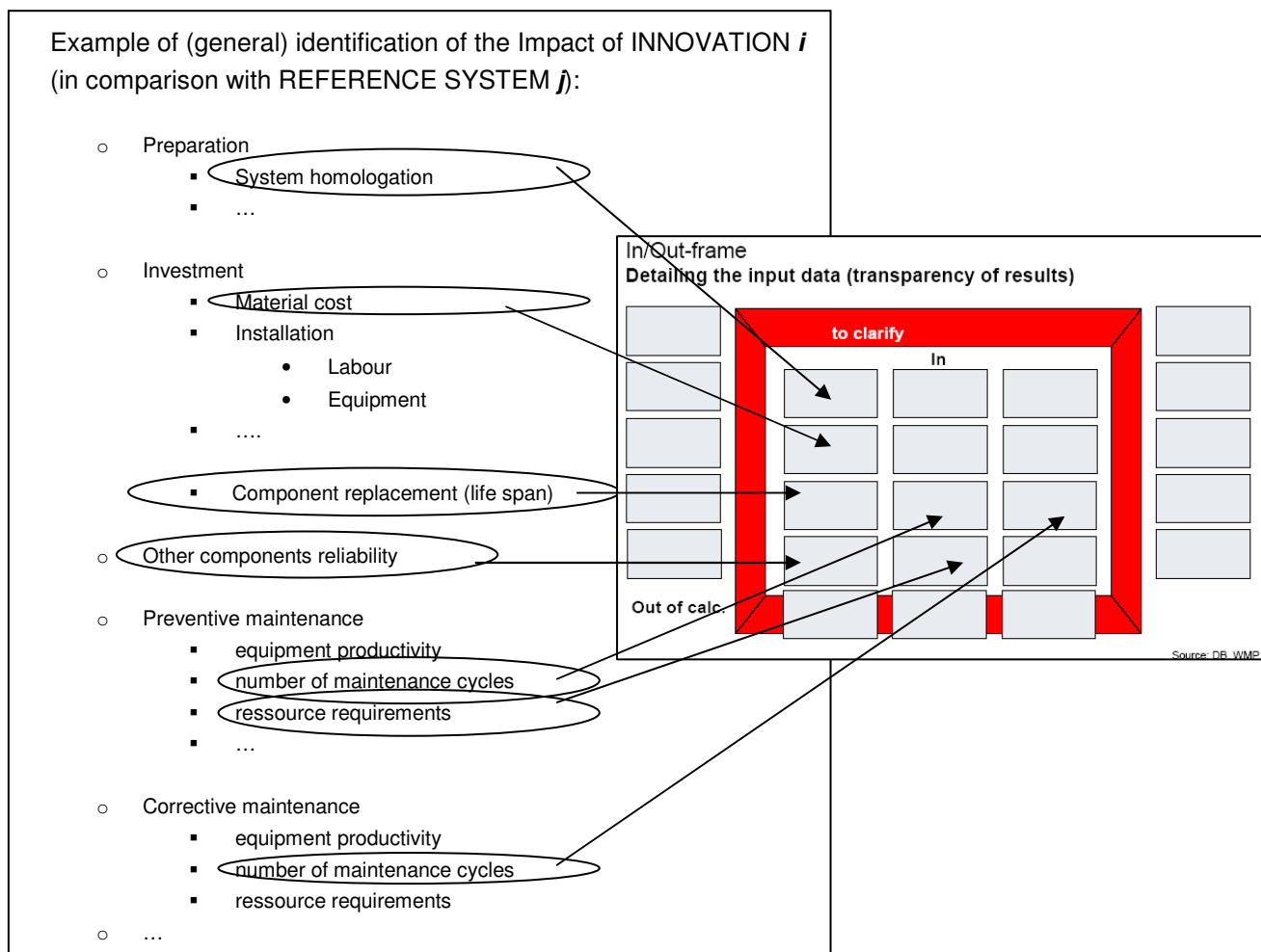
The first step (A –Definition) is the identification of each innovation to be assessed, a definition of its impact (compared with current situation - failure modes, component lifetimes,..) and a definition of the reference solution with which the innovation will be compared with.

In terms of LCC, generally “hardware” innovations act in:

- Maintenance and renewal cycles/intervals (e.g. decreasing failure rates)
- Maintenance and renewal works unit costs
- Investment costs
- Availability
- Residual / recycle values

Other “software” innovations can also be found (e.g. acting in maintenance tolerance criteria) even if the evaluation of the impact of such measures can be far more complex. It should be pointed out that some innovations might go beyond the reduction of the life cycle costs of the system itself (e.g. if the solutions aim to improve rail market attractiveness, by for example increase comfort or increase interoperability): in these cases the analysis should go beyond pure LCCA and be assessed within the framework of a broader cost-benefit analysis.

The definition of the impact of each innovation should refer to what is new (general description) and an identification of which specific cost elements does the innovation affect (including the breakdown of this effect) within a reference cost matrix, as described in the following example (Figure 4). The result can be visualized as an in/out frame (Figure 4) where one can identify those cost elements that will be part of the LCC calculation and, as a result, will require a detailed clarification and possible breakdown (if applicable).



**Figure 4 - Identification of cost elements affected by the innovation (to be included on the LCC analysis)**

To address this question for each INNTRACK innovation, a questionnaire has been prepared (by DB) and sent to SP2 to 5, with the following structure and questions:

1. Description of the reference system: track elements (alignment, track construction and subgrade), boundary conditions and track condition
  - Definition of reference system: a detailed introduction and explanation of the reference system (technical structure)
  - Description if standard system is used or a certain track or track section
  - Description of the dimensions of the track/track section
  - If no reference system is used, description of a fictitious case with defined parameters as reference system
  - Definition of boundary conditions of the system (loading e.g. collective, radius curve, etc)
  
2. Description of the optimisation / innovation
  - Description if an optimised reference system or components or technology has been developed
  - Explanation of the optimisation (innovation, improvement)
  - Description of the comparison of existing system/component with new or improved system/component
  - Explanation of what is the optimisation aimed for and why
  - Description of the strategy, method and process of the optimisation
  - Description of the experiences with optimisation
  - Explanation of the expected benefits of the optimisation
  
3. Description of the future requirements
  - Description of future requirements (if any)
  - Description of which field, components are concerned by these requirements (e. g. improvement of rams-parameters or e.g. increase of traffic volume, load tonnage, axle load)
  - Description of the expectations of the requirements

Additionally, to support Step A (Definition of innovations) a reference Product Breakdown Structure (PBS) has been sent to SP2-5 (in order to collect the required data to move to step B – Building of the LCC models within WP6.5), proposing the following reference (minimum) structure:

- Track elements - Alignment
  - Gradient
  - Straight line/Curve radius
    - <300 m
    - 300 - 700 m
    - 700 - 1500 m
    - 1500 - 5000 m
    - >5000 m
  - cant of the track
  - transition curve clothoid
  - sinusoid
  - cubic parabel
  
- Track elements - Track construction
  - superstructure type (ballast, slab track)
  - rail
    - type
    - profile
    - inclination
    - steel grade

- sleeper
  - type (steel, concrete, S&C hollow)
  - mean span
- fastening
- pads
  - type
  - dynamic stiffness
- ballast
  - type
  - thickness
- components of a S & C Blade
  - Frog
  - stock rail
  - check rail
  - point rod (mechanic/ hydraulic)
  - switch point machine
  - Monitoring system
  - Others
- Track elements - Subgrade
- protective layer
  - sub-layer
  - frost protective layer
- earthwork
  - embankment
  - cut
- construction
  - bridge
  - tunnel
- transitions
  - bridge/embankment
  - tunnel/embankment
  - bridge/tunnel
  - level crossing
- drainage
  - ditches
  - deep drainage
  - special characteristics

The processing of the questionnaire results is presented and discussed in WP6.5, deliverable D.6.5.1. As an example, Figure 5 shows the results of the questionnaire PBS/CBS reference system versus innovation for an innovation performed within SP4.

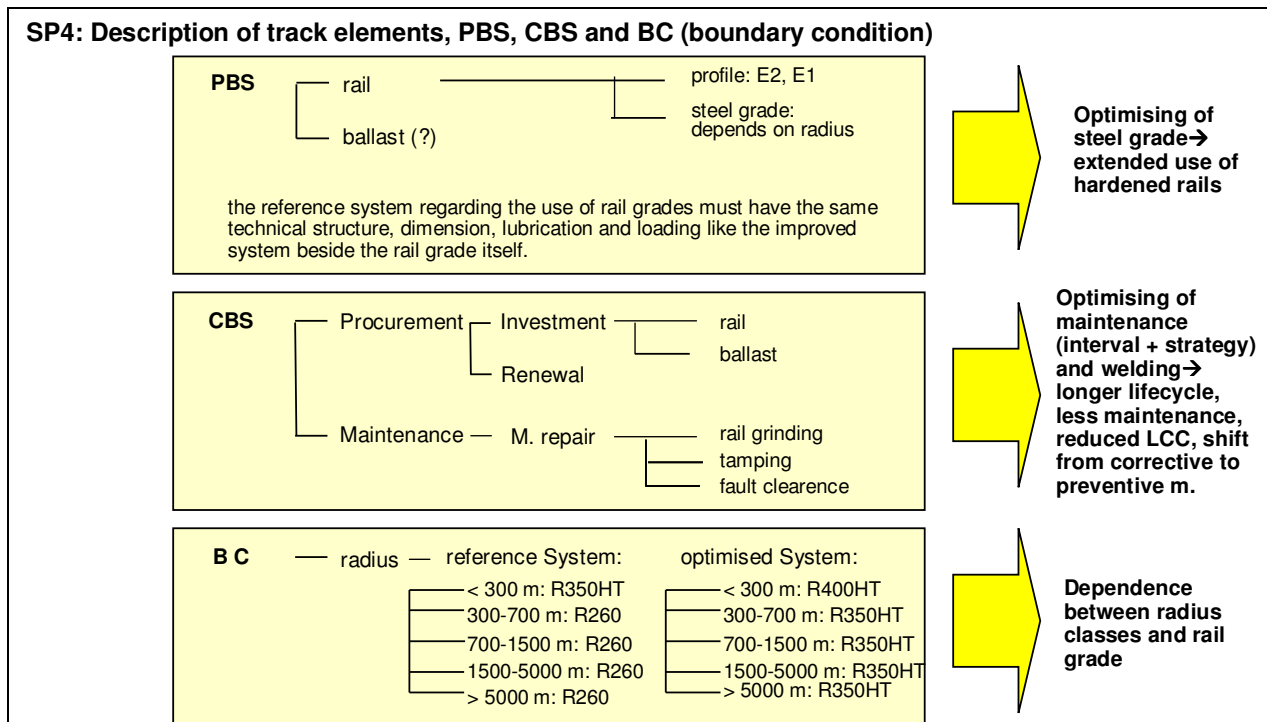


Figure 5 - Example of questionnaire feedback for an SP4 innovation. More detail in WP6.5 (D.6.5.1)

The next sections discuss the general requirements to perform Step B (Building of the LCC models) and Step C (Calculation and Sensitivity Analysis) within WP6.5.

### 3.3 Step B - Building of the LCC models

#### 3.3.1 General structure

To be able to compare innovations (developed within SP2-5) with reference systems, a modular PBS and CBS must be built for each case. This requires first to define the technical/functional reference structure starting from an analysis of the cost elements that should be “affected” by the innovation, as referred in previous Step A, paying attention to the following aspects:

- The definition of the PBS of reference case and innovations should be limited to the minimum number of components that are directly affected (maintenance needs and/or technical lifetime) when comparing the different alternatives (e.g. if different rail steel grades are being assessed, the fastening system or the sleeper should be part of the model only if there are quantitative figures - output from degradation functions- on the change on the LCC of these components depending on the rail steel grade used).
- Equations should include maintenance cycles defined through RAM parameters (MTBF, MTTR,...)
- Proper boundary conditions should be defined and written for each case. For the reference systems it is fundamental to define a priori the origin of the RAM and cost values used for comparison, particularly what assumptions are assumed regarding the most relevant conditions, such as:
  - The maintenance method (e.g. for tamping, assumptions regarding tamping equipment, in-house/outsourced, quality after tamping and measurement method -absolute or relative-, stabilization and profiling, material, etc.)
  - Possession time considered
  - Length of the section where the intervention took place

The macro-structure of the CBS must follow the definitions of current standards, particularly current EN-50126. The CBS breakdown levels must be built in accordance with the quality and availability of cost data (i.e. if for tamping works only average tamping cost figures are available, the CBS should not consider breaking down tamping cost into equipment/material/personal costs for this particular activity).

The optimum level of desegregation of a given activity (e.g. tamping) should be defined as the level in which:

- Cost data is available and reliable, and
- Cost data can have a direct relationship with the identified drivers or parameters that changes with the innovation (e.g. tamping cycles)

The abovementioned means that if for example “average tamping cost” can not have a direct relationship (formula) linked with the tamping activity itself, a breaking down of this activity is required. This could be the case if only part of the “average tamping cost” can be considered variable with the work performed: for instance for an in-house maintenance policy, while material costs (ballast in this case) can be assumed as variable, other costs such as *equipment costs* and *labour costs* might have an important part of fixed costs, which requires breaking down to material/equipment/labour and breaking down equipment and labour into fixed and variable parts.

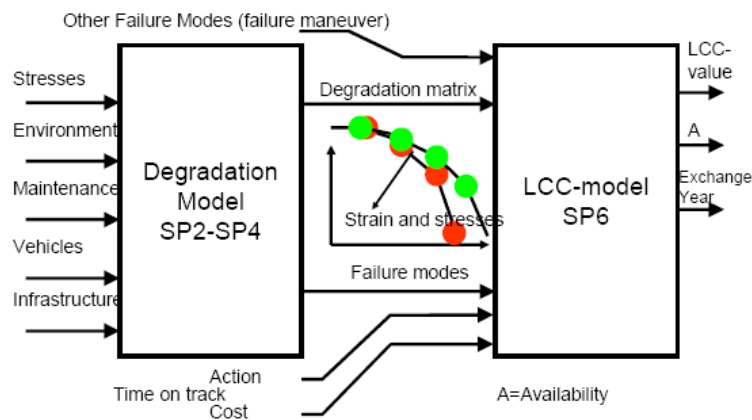
### 3.3.2 RAM parameters (output from SP1 to SP5)

Required RAM parameters as input to WP6.5 LCC models must be defined in an early step by each SP, in order to support the building of the LCC cost matrix.

As a first step, technical boundary conditions described through the questionnaire of Step A – Definition should be detailed. Main RAMS boundary conditions within railway track have been presented in deliverable D.6.3.1. Within the template sent as questionnaire to assess SP2 to SP5 innovations, the following technical boundary conditions have been referred as example:

- Requirements
  - service life-time (unit of the life cycle)
  - periods
  - restrictions during installation
  - regarding availability
  - regarding reliability
  - regarding maintenance
  - regarding safety
  - construction with best LCC
    - low investment
    - high availability
    - high maintenance
- Traffic
  - load (MGT/unit of time) / type of line
  - maximum speed on the track section
  - type of line
  - traffic volume
- Environment
  - solid-borne-sound
  - sound insulation
  - atmospheric influence
  - national requirements
  - special characteristics

After identifying the relevant boundary conditions, RAM parameters (MTBF, MTTR,...) should be quantified provided by SP2-SP5 with the support of degradation models applied within each SP or through generic models used by SP1 modelling group, as schematically represented in well-known INNOTRACK Figure 6.



**Figure 6 - Degradation models output and link with SP6 LCC models**

### 3.3.3 Cost data for INNOTRACK calculations

#### 3.3.3.1 Structure of cost data

LCC analysis to be performed in WP6.5 will compare innovations with reference systems: since innovation impact will usually be defined in terms of relative degradation (e.g. difference in maintenance cycles, ...) comparing with the reference system, cost data for reference system plays a key role on the assessment of the economical impact of innovations (in relation to total system's costs). Since degradation assumptions are in some occasions difficult to establish, it is crucial to have solid confidence on the reference cost data applied, to minimize uncertainties.

Confidentiality constraints and the known heterogeneity of cost data among European partners (as shown in LICB study for instance) led INNOTRACK SP6 working group to define a two-parts approach for LCC modelling regarding cost data usage within WP6.5:

- An approach using INNOTRACK calculation with “homogenised” cost figures (high-level costs)
- An approach where the LCC models are developed and used by each IM with national data, allowing more detailed cost figures and therefore and higher degree of desegregation of the CBS.

The first approach (INNOTRACK calculations) requires the building of a cost database where information of each IM/stakeholder is compiled in order to identify the whole variability of costs. The data to be collected for the INNOTRACK Cost Database should preferably:

- Consider high-level costs with less confidentiality restrictions (e.g. general “cost of tamping” or “cost of grinding -0,1mm”)
- To include average value reference cost (reflecting the average cost of the network, for the given maintenance and renewal activity or sub-activity) is recommended. It is recommended to avoid the use of costs that might represent a specific sub-optimal practice (i.e. with inefficiencies).
- Additionally, to be able to make sure that the objective of INNOTRACK project is accomplished (reduction of 30% in existing Track Life Cycle Costs) it is advisable to collect also “best practice” costs within each IM/stakeholder. Innovations should also be compared with best practices.
- Therefore, when applying deterministic analysis, two calculations should be performed as INNOTRACK calculations: calculations with average costs and with best practices costs.

As for the structure of the INNOTRACK “high-level” cost database, SP6 working group have decided to use a desegregation level at least similar to the following NR template, which represents a good compromise on the relation between confidentiality vs usefulness of data.

<b>Maintenance Volumes</b>		
<b>Asset</b>	<b>Activity</b>	<b>Units</b>
Inspections	Visual Inspection	track km
Inspections	Ultrasonic - Manual	track km
Inspections	Ultrasonic - Train based	track km
Inspections	Geometry - train based	track km
Rail	Rail change	rail km
Rail	Rail transpose	rail km
Rail	Rail change - defects	rail km
Rail	Weld repairs	# repairs
Rail	Grinding	track km
Rail	Lubrication	track km
Rail	Rail adjustment	track km
Rail	Fish plate lubrication	track km
Rail	IBJ replacment	#IBJs
Sleeper	Re-sleeper (reactive)	track km
Sleeper	Replace pads and insulators	track km
Sleeper	Long timber (M)	metres
Ballast	Ballast reprofile	track km
Ballast	Wet bed removal	track km
Ballast	Tactical reballast	track km
Geometry	PL tamping	track km
Geometry	Stoneblowing	track km
Geometry	Geometry - manual	track km
S&C	Half set replacement	#switches
S&C	Crossing replacement	#crossings
S&C	Crossing weld repair	#crossings
S&C	Replace timber bearers	#bearers
S&C	S&C Tactical reballast	#units
S&C	S&C tamping	#units
S&C	Manual S&C geom correction	#units
<b>Off Track Total</b>		
Drainage	Drainage	
Fencing	Fencing	
Incident Response	Incident Response	
Level crossings	Level crossings	
Vegetation	Vegetation	
<b>Renewal Volume</b>		
<b>Plain line (km)</b>	RSB (Rail, Sleeper and Ballast)	
	Rail	
	Sleeper and Ballast	
	Tactical resleeper	
	Ballast cleaning	
<b>S&amp;C (units)</b>	S&C renewal	
	Abandonment	

**Table 2 - Level of detail suggested for costs database, based on NR template1**

Data for the cost database should be gathered through questionnaire after defining the structure of LCC models within WP6.5. The cost data should have a common price index base and refer to 2008.

As mentioned previously, it is essential to identify the boundary conditions associated to each of the costs of maintenance or renewal activities, since some factors such as the maintenance methods or possession time

<sup>1</sup> The template will still be adjusted for INNTRACK calculations (after validation of all IM within SP6).



are known to have an important impact. Table 3 presents a draft of possible template to be filled by each IM of the SP6 LCC modelling group.

Asset	Maintenance Volumes		“Average” (network) cost		“Best practice” cost	
	Activity	Units	Cost (euros)	Description of boundary conditions	Cost (euros)	Description of boundary conditions
Rail	Grinding	track km	.....	Maintenance method: .....	.....	Maintenance method: .....
				Possession time: ....		Possession time: ....
				Length of intervention: ....		Length of intervention: ....
				....		....
				....		....
...	...	...	...	...	...	...

**Table 3 - Example of possible template for Cost data compilation (questionnaire)**

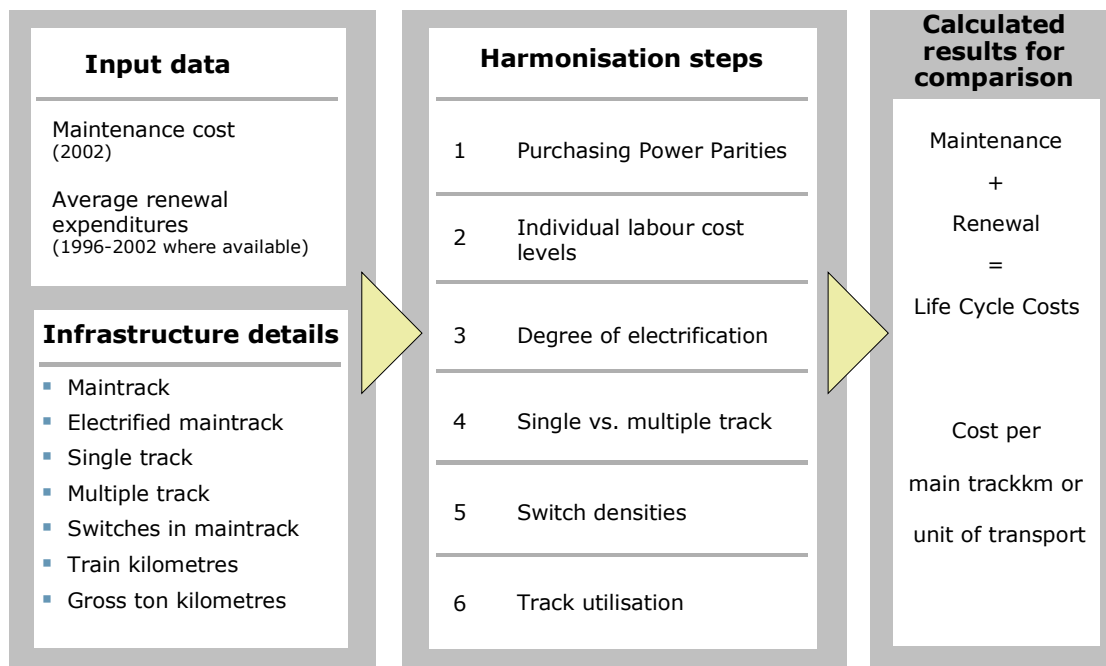
An important issue regards the need to define the way the access of data (provided by stakeholders) will be addressed. This issue will be agreed within the LCC modelling group and is out of the scope of this report.

Finally since innovations are solutions with a reduced level of implementation one should bear in mind the need to have adequate costs inputs related to the early stages of design, development and installation, where important costs of testing and homologation can be involved. The degree of application of the innovation is one boundary condition here, since possible scale effects can reduce the relative importance of these costs, depending on the extend to which the innovation is adopted.

### 3.3.3.2 LICB experience regarding cost homogenisation

The costs (average and best practice) to be used within each LCC model should be the result of an “homogenisation” process, taking into consideration the costs from different countries collected on the database. Concerning this homogenisation process, it was decided by INNOTRACK SP6 working group to refer to UIC experience on the LICB project.

UIC LICB project addressed the cost of railway infrastructure among several European railway administrations, as well as Japan and United States. The results have shown an important dispersion and a specific methodology to homogenise cost data has been developed to be able to compare the maintenance and renewal costs figures among the different countries. The harmonisation steps are shown in Figure 7.

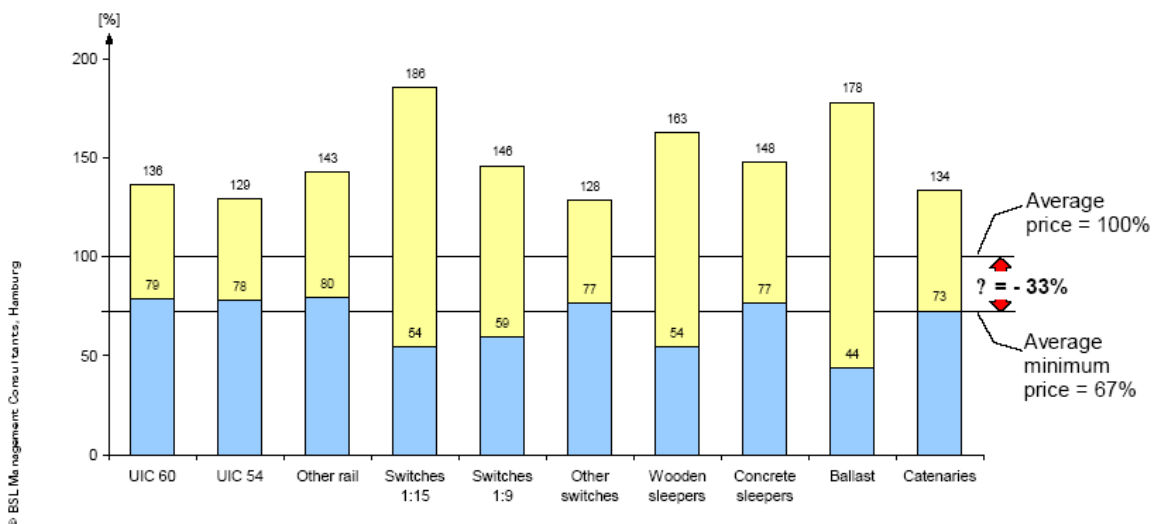


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**Figure 7 - LICB harmonization steps**

For INNTRACK cost database homogenisation, particular attention should be paid to material costs and labour costs.

Figure 8 shows that there is an important variability among the purchase cost of most of the track components: according to LICB, the variations on material costs are in the range of +/- 30% among the countries involved on the benchmark.



**Figure 8 - Relative variation of the cost of track components in Europe, according to LICB study**

Source: provided by UIC

Concerning labour<sup>2</sup> costs, LICB have proposed coefficients of adjustment with a variability that can be up to 10%, as shown in next Figure 9 (labour factors). The reference labour cost considered in this case is of 40.000 Euros per full time employee and year.

3	Anonym	C	D	E	F	N	Q	U
40	<b>LABOUR COSTS</b>							
41	Labour factor	1,08	0,96	1,13	0,96	0,84	1,12	1,06
42	Harmonisation factor (Maintenance, labour costs)	1,05	0,97	1,09	0,97	0,90	1,08	1,03
43	Harmonisation factor (Renewal, labour costs)	1,04	0,99	1,03	0,99	0,95	1,04	1,02
44	Maintenance total [1.000 Euro/main trackkm]	22,14	20,49	25,36	35,59	45,83	28,24	16,73
45	Maintenance for electrification [1.000 Euro/main trackkm]	1,54	1,50	2,28	4,99	2,25	0,00	0,88
46	Renewal total [1.000 Euro/main trackkm]	12,89	6,97	31,62	20,87	52,30	32,08	20,00
47	Renewal for electrification [1.000 Euro/main trackkm]	1,71	1,35	1,14	5,44	3,15	0,00	1,05
48	Maintenance excl. electrification [1.000 Euro/main trackkm]	20,59	18,99	23,08	30,60	43,58	28,24	15,85
49	Renewal excl. electrification [1.000 Euro/main trackkm]	11,18	5,62	30,49	15,43	49,16	32,08	18,95

Figure 9 - Partial view of LICB spreadsheet with an example of different labour cost factors applied.

Source: provided by UIC

Accordingly, also the LICB results concerning the impact of relevant boundary conditions such as possession time and track utilisation should be taken into consideration. Figure 10 and Figure 11 show the impact of these two factors on average maintenance and renewal costs.

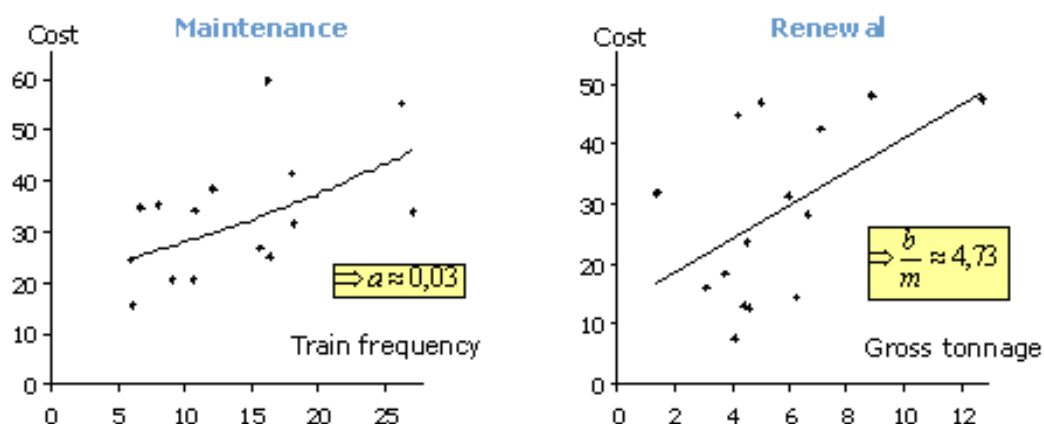
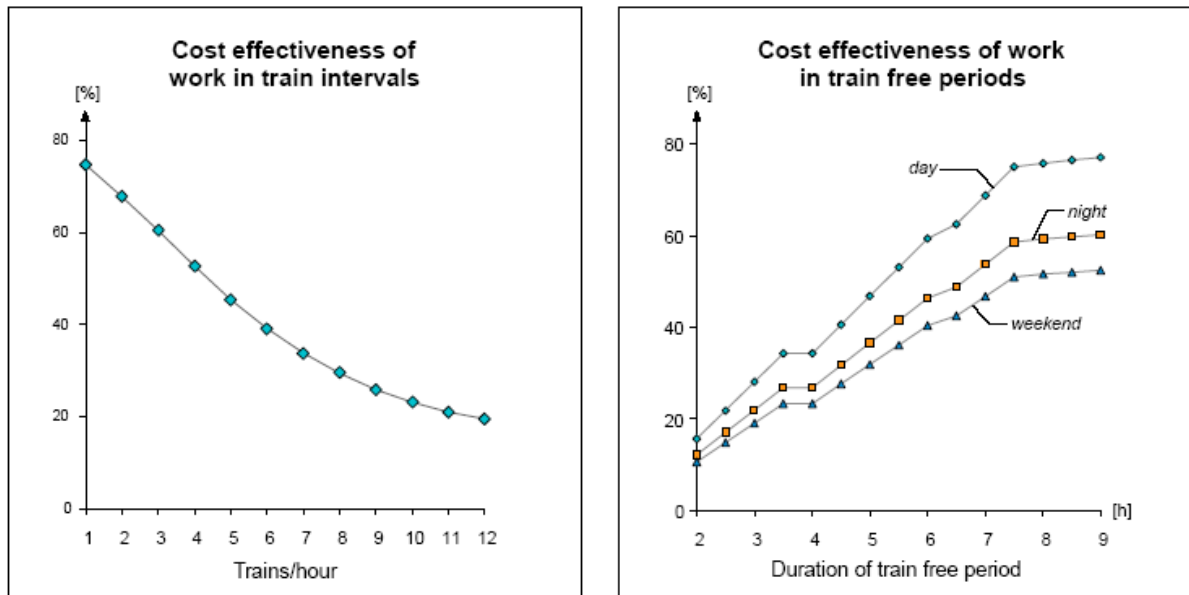


Figure 10 - Impact of track utilisation on maintenance and renewal costs, according to LICB study

Source: provided by UIC

<sup>2</sup> According to LICB, labour represent a significant part of total M&R costs (up to 60% of the costs of main maintenance works and 30% of the costs of renewal works).



Source: NS-RIB

**Figure 11 - Example of relationship between cost effectiveness and possession time**

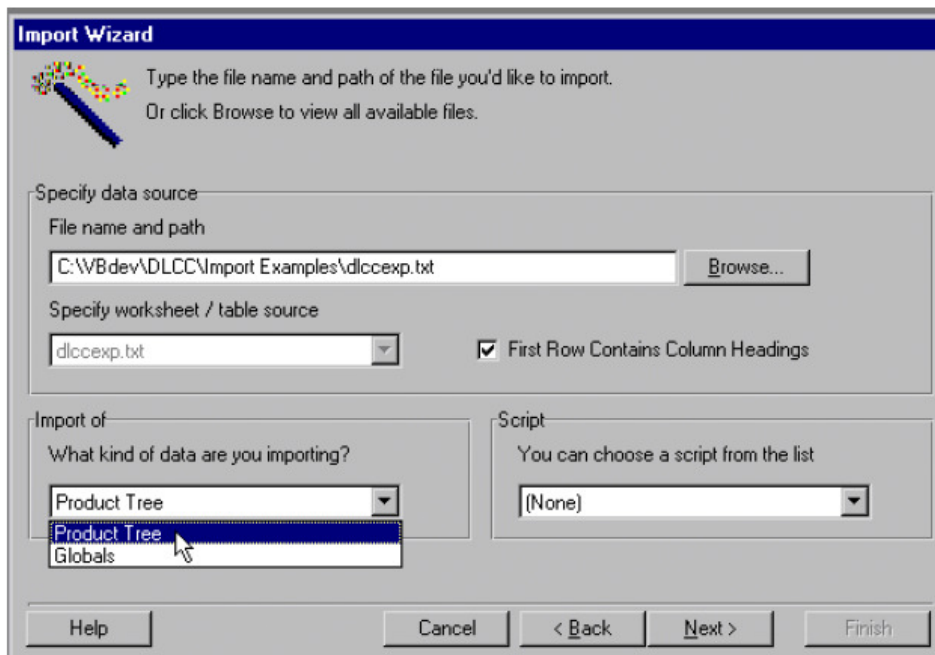
Source: provided by UIC

### 3.3.3.3 Managing cost data within LCC models (with the D-LCC software)

Within WP6.5, modular LCC models (for innovations and reference systems) will be prepared and applied with INNTRACK cost figures, after the aforementioned harmonisation procedure.

In parallel, the models will be used by each IM (participating in the SP6 LCC modelling group) to perform calculations with (detailed and/or confidential) national cost data. The models should provide a defined cost structure that allows an easy incorporation of the cost information. Cost information can be easily imported with the chosen<sup>3</sup> software D-LCC associating each unit cost to a given *global variable*. The import of the required variables can be easily performed using the “import wizard” command of the D-LCC software and selecting import “globals” (Figure 12).

<sup>3</sup> After benchmark and testing of different software, deliverable D6.2.2/3



**Figure 12 - D-LCC Import wizard main screen**

To put this into practice it seems recommendable to have cost elements of the models using an easily understandable nomenclature. As an example, a list of variable numbers could be associated to each of the costs to be used (previous Table 2). An excel spreadsheet should be sent with an indication of the global number, the type of cost and an explanation of the cost involved, as shown on the example of Figure 13.

	Global nº	Cost element	Description of cost	Boundary conditions
Maintenance activity →	G205	Grinding cost 0,3	Cost of grinding per km of track, with average metal removal of 0,3mm	Track possession: 4 to 5h ....
Material /component cost →	G314	....	....	....

**Figure 13 - Example of variable “Global” numbering to facilitate cost import.**

The necessary improvements of the import functionality of the software have been identified (after D6.2.2/3) and sent to the software developer: the new D-LCC version with the required modifications should be available at the end November 2008.

### 3.4 Step C – Calculation and Sensitivity analysis

#### 3.4.1 Required innovations (after D.6.2.2/3) for LCC calculation within WP6.5

D6.2.2/3 evaluated existing LCC tools. The work of the SP6 LCC modelling group defined the software D-LCC as best suited for INNTRACK calculations, on the condition that the provider (ALD) agreed to introduce some key improvements.

After further D-LCC analysis among SP6 members, it was proposed to enlarge the D-LCC improvements requirements. These include at present the following:

General improvements:

- Incorporate a Monte-Carlo simulation (probabilistic output)
- Enable target cost as results
- Incorporate the calculation of Annuity factor
- Improvement on the output results (figures, reports to export to excel)
- Allow the possibility to “lock” a given model so the database is not changed/deleted by mistake
- Improve comparability and “check process” of inputs and detection of errors
- Improve the importability of variables from database
- Introduce an “undo” function to facilitate the input of data

Global variables:

- Extend the name field and allow multiple name changes (when importing a global only pay attention to the reference number).
- Add a column on global variables to include the source of the data
- Add a column for date

Formula:

- Extension of the character restriction within the formulas
- Make possible to lock the formulas (to avoid possible accidental changes among different IM users)
- Incorporate function “round up”

CBS:

- Improve distribution functions / time dependent functions, in order to allow different intervals among one item
- Enable introducing stochastic variables
- Improve the link of CBS elements (e.g. maintenance) with the PBS (components)

Tables

- Enable the import of a table (e.g. from excel)
- Enable table numbering starting from 0 (e.g. TBL(0,...))

One of the key aspects that can constitute a powerful innovation on railway track LCC modelling is the development of a probabilistic LCC analysis (instead of common deterministic sensitivity analysis), using the required Monte-Carlo simulation toolbox. The next section presents some guidelines on how to apply this probabilistic LCC analysis and its usefulness to assess INNOTRACK innovation.

### 3.4.2 Probabilistic analysis for INNOTRACK LCC estimations using Monte Carlo Simulation

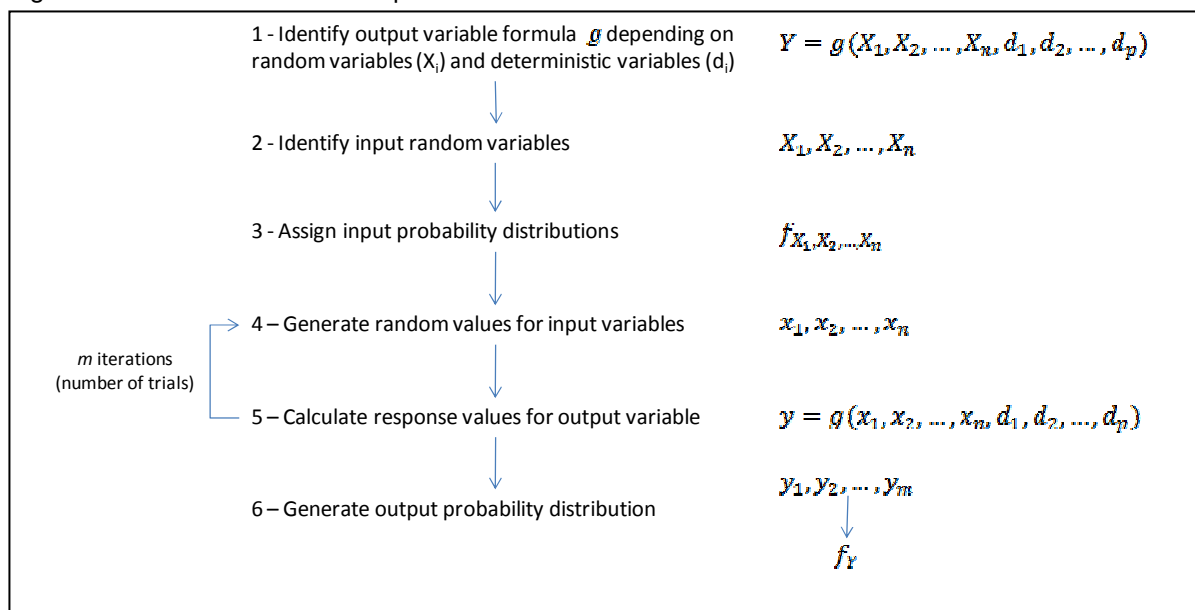
Although sensitivity analysis is performed very often, LCC estimations are usually based on deterministic values for each input variable considered, lacking more knowledge on the robustness of these estimations and associated design and maintenance decisions. Therefore, a more comprehensive method to assess the uncertainty associated with input variables is needed.

The Monte Carlo simulation technique is a largely used method to assess uncertainty associated with any variable (output variable) that depends on a set of variables (input variables), knowing the uncertainty associated with them. Monte Carlo simulation involves assuming that input variables are no longer deterministic but random variables, and thus defining proper probability distributions to model these variables. In fact, this method has been gaining popularity, thanks to modern computer power, replacing more straight-forward methods as sensitivity and scenario analysis.

Note that uncertainty can never be entirely eliminated as most systems are open systems in interaction with an external environment, and there will always be a lack of information or knowledge with respect to this interplay. In the Railway infrastructure, the degradation process of its components of track and other systems is definitely the crucial uncertainty source, and associated costs are related with non-availability of infrastructure. Therefore, the uncertainty of RAM (Reliability, Availability and Maintainability) parameters may be the most relevant in assessment uncertainty related with of LCC estimations. Nevertheless, other variables (e.g. maintenance and construction costs, interest rate) may be also important sources of uncertainty, whereas some of them may not influence to a greater extent the total LCC uncertainty.

As mentioned before, to perform Monte Carlo simulation proper probability distributions should be assigned to input random variables. Two different approaches are typically taken: expert-based estimations and historical data based estimations. Historical data based estimations are usually performed using statistical methods, as goodness-of-fit tests and independence tests<sup>4</sup>.

Next Figure 14 illustrates the main steps of Monte Carlo simulation method.



**Figure 14 - Monte-Carlo simulation method**

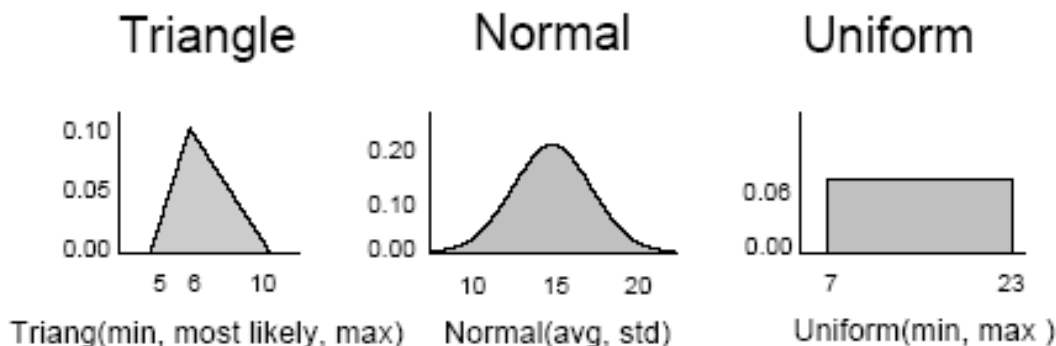
The first step is identifying the output variable formula, meaning defining the mathematical equation that estimate the output variable ( $Y$ ) given the input variables. In the second step, the input random variables  $\{X_i\}$  are identified, assuming that the possible remaining variables are deterministic ( $d_i$ ). Afterwards, probability distributions are assigned to input random variables. Note that this step may require comprehensive data analysis, goodness-of-fit tests and independence tests, in order to define the joint probability density function of the input random variables  $f_{(X_1, X_2, \dots, X_n)}$ . In the fourth step, random number generation is processed for each input variable, whereas in the fifth step an output value is calculated using the mathematical relation defined in step 1. The fourth and fifth steps are then repeated a high number of times so that the generated probability density function (sixth step) is reliable<sup>5</sup>. Note that each time, different random numbers for input variables are generated, and a new output value is calculated in each iteration, and therefore a set of values for the output variable is obtained  $\{y_1, y_2, \dots, y_m\}$ . In the sixth step, the

<sup>4</sup> Independence tests to test if input random variables are mutually independent are particularly important so that the generation of random numbers is facilitated, as the joint probability density function factorizes into the product of their marginal density functions.

<sup>5</sup> The main foundation of the Monte Carlo simulation reliability is the Law of Large Numbers, which states that the frequency of occurrence of a random event converges to a limit called probability of that given event, as the number of trials increases. Therefore, it can be demonstrated that the resulting frequency distribution of output values converges to its real distribution, if the number of trials increases.

probability density function of the output variable is generated using the set of values for the output variable. Note that goodness-of-fit tests may be Monte Carlo simulation method can deal with all kinds of input (discrete, continuous, stochastic, fuzzy, etc). Many runs are made using a random generator (each run delivers an independent observation).

The most typical probability distributions used to model input variables are: the uniform distribution, the triangular distribution, the normal distribution (see Figure 15), and also the exponential distribution, the Weibull distribution and the log-Normal distribution.



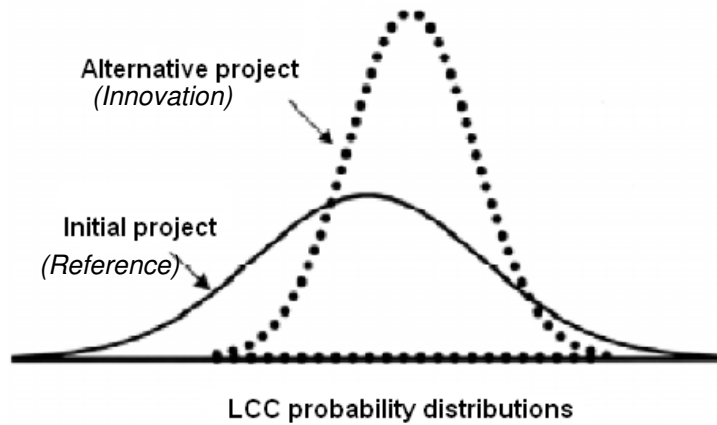
**Figure 15 - Example of common probability distributions.**

Expert-based estimations are usually modelled as triangular random variables, similarly to what happens in PERT (Project Evaluation and Research Technique), or using a beta distribution. An approach used to set the distribution parameters is the three-estimate approach, consisting of asking an expert to make three estimations: a most likely value, an optimistic value and a pessimistic value, and using them to calculate distribution parameters. The most likely value should be seen as the most realistic estimation, whereas the optimistic and pessimistic values are unlikely but possible if everything goes well or badly respectively. Concerning historical data based estimations, the probability distribution which best fits the historical data should be used to model that input variable.

The Monte Carlo simulation method may be understood as a variance-reducing technique of simulation, and in this context more complex approaches can be used to generate random numbers, combining it with stratified methods of sampling. Nevertheless, modern computer power permits to run Monte Carlo simulation without using these stratified methods of sampling.

Finally, it is important to mention that this technique may be extremely helpful in order to compare alternatives projects or design and maintenance decisions. In these cases, Monte Carlo simulation output would be for example the probability distribution for the LCC of a project (or its net present value), which should be compared to the probability distribution for the LCC of an alternative project, also given by Monte Carlo simulation. Therefore, the probability that the alternative project LCC exceeds the initial project LCC can be estimated.





**Figure 16 - Example of LCC probability distributions output.**

### 3.4.3 Example of application of probabilistic analysis

Now, a very simple example will be discussed in order to show how the Monte Carlo simulation can help to support a decision-making process when dealing with different design/operating options. Imagine we want to choose one design/operating option from 2 alternative solutions from a life-cycle cost perspective (life-cycle, LC, equal to 3 years), using a probabilistic approach:

Imagine we know that the main elements of total life-cycle cost for those solutions are:

- The initial cost for preliminary engineering and construction - **IC**
- Maintenance costs for each year (**y**) - **MC**
- Operating costs for each year (**y**) - **OC**

In the Figure 1, the first step to run Monte Carlo simulation was identifying the output variables formula, depending on random variables and deterministic variables. As we are analyzing 2 alternative solutions from a life-cycle cost perspective, we have to include the main elements of total life-cycle cost in the formula of the **LCC** (output variable), respectively discounted given a discount rate (**r**).

$$LCC = \sum_{y=0}^{LC} LCC(y) = IC + \sum_{y=0}^{LC} \frac{MC(y) + OC(y)}{(1+r)^y}$$

Next Table 4 shows the expected values for each variable presented above for both solutions (A and B). Note that solution A has an expected **LCC** value lower than solution B. A deterministic approach would suggest to choose solution A as it has a total life-cycle cost.

Solution A	Year			
	0	1	2	3
IC (M€)	40	0	0	0
MC (M€)	10	10	10	10
OC (M€)	6	6	6	6
LCC	56	15	14	13
r	6%			
LCC	99			

Solution B	Year			
	0	1	2	3
IC (M€)	60	0	0	0
MC (M€)	8	8	8	8
OC (M€)	4	4	4	4
LCC	72	11	11	10
r	6%			
LCC	104			

**Table 4 - Expected LCC estimations for solution A and solution B (deterministic approach)**

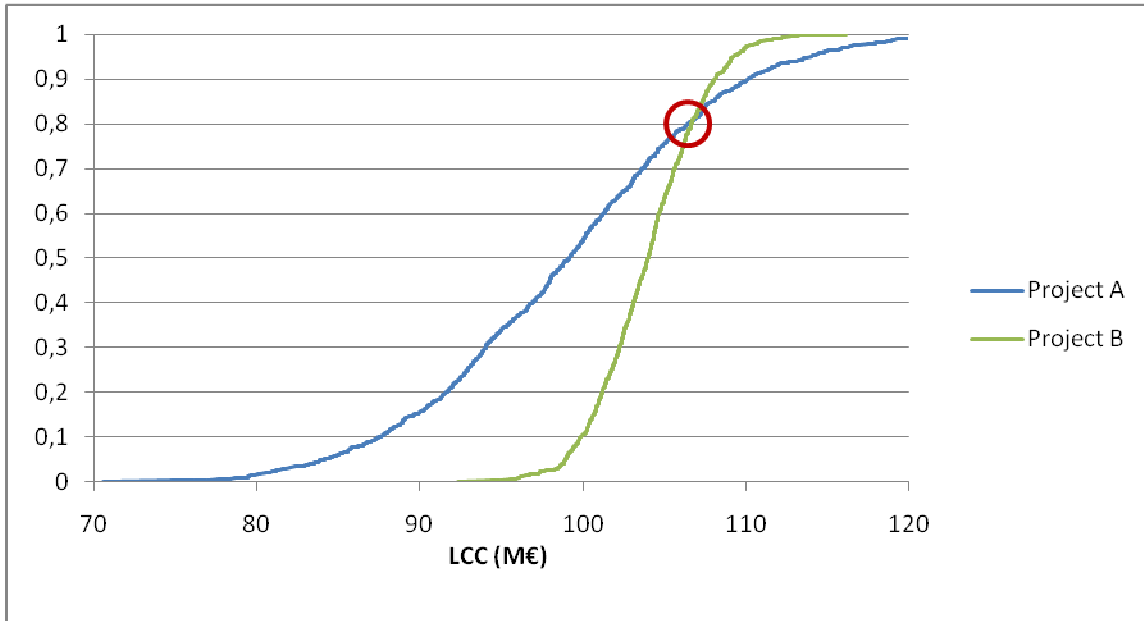
However, the deterministic approach does not take into account the uncertainties associated with the estimations for each variable. In this example, each variable will be considered stochastic, though some variables could be modelled as deterministic variables. Therefore, we will have to quantify the uncertainty associated with each variable using the Monte Carlo simulation technique, by assigning input probability distributions to random variables based on an expert estimation or historical data.

In this example, we will assume that:

$$\begin{cases}
 \text{Project A} & \left\{ \begin{array}{l}
 IC \sim \text{Uniform} (a = 30; b = 50) \\
 MC (y) \sim \text{Normal} (\mu = 10; \sigma = 3) \\
 OC (y) \sim \text{Normal} (\mu = 6; \sigma = 2) \\
 r \sim \text{Uniform} (a = 4\%; b = 8\%)
 \end{array} \right. \\
 \\
 \text{Project B} & \left\{ \begin{array}{l}
 IC \sim \text{Uniform} (a = 57; b = 63) \\
 MC (y) \sim \text{Normal} (\mu = 8; \sigma = 1) \\
 OC (y) \sim \text{Normal} (\mu = 4; \sigma = 1) \\
 r \sim \text{Uniform} (a = 4\%; b = 8\%)
 \end{array} \right.
 \end{cases}$$

Note that Maintenance costs for each year  $(y) - MC (y)$  – are independent random variables, and that operating costs for each year  $(y) - OC (y)$  – are also independent random variables for each solution. Moreover, initial cost and discount rate are also assumed independent random variables for each solution.

Running Monte Carlo simulation for  $m = 1000$  trials, we get a collection of  $\{x_1, x_2, \dots, x_m\}$ , that is a sample of the real distribution of the output variable  $(Y)$ . Then, we may generate the output probability distribution. Normally cumulative distribution functions are computed, instead of density probability functions, to limit computational difficulties.



**Figure 17 - Cumulative distribution functions for solution A and B obtained from Monte Carlo simulations.**

As seen in Figure 17, solution A has a higher life-cycle cost (LCC) than solution B for percentiles higher than approximately 81%. Note that, in terms of expected values (percentile 50%), table 2 has showed that solution A has a lower LCC (99 compared to 104). In the simulation these values are slightly different as Table 5 below shows.

	LCC (M€)		
Statistics	Solution A	Solution B	A-B
Minimum	70,55	92,35	-21,80
Maximum	131,24	116,12	15,12
Average	98,99	103,98	-4,99
Std Deviation	8,90	3,24	5,67
Percentile			
5%	84,12	98,92	-14,81
10%	87,52	99,85	-12,33
15%	89,62	100,66	-11,04
20%	91,60	101,18	-9,58
25%	92,94	101,77	-8,82
30%	94,04	102,23	-8,19
35%	95,37	102,66	-7,30
40%	96,90	103,10	-6,20
45%	97,97	103,52	-5,55
50%	99,16	104,00	-4,84
55%	100,15	104,35	-4,19
60%	101,25	104,65	-3,40
65%	102,55	105,15	-2,60
70%	103,65	105,62	-1,96
75%	104,85	106,15	-1,30
80%	106,46	106,65	-0,19
85%	107,94	107,35	0,59
90%	110,10	108,06	2,05
95%	113,99	109,19	4,79

**Table 5 - Statistics for Solution A and Solution B obtained from Monte Carlo Simulation**

Although the deterministic approach (expected values) indicates to choose solution A (99 < 104), its LCC has a higher uncertainty than solution B LCC, and there is an estimated risk of 19% (100% - 81%) that solution A LCC may be higher than solution B LCC.

## 4. Conclusions

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This deliverable has discussed the requirements for INNOTRACK LCC modelling (to be performed within WP6.5), addressing the following questions:

- Building of LCC models
- The reference costs database
- Cost harmonisation procedure
- LCC Calculation and sensitivity analysis (through probabilistic analysis).

Concerning the building of the LCC models, the general procedure has been presented, as well as the structure of the questionnaire developed (within WP6.5) to gather information both on the definition of the cost matrix and on the definition of the technical boundary conditions of the calculations.

As regards the cost data to be used in LCC calculations, a two level approach is suggested:

- An approach using INNOTRACK calculation with “homogenised” cost figures (high-level costs)
- An approach where the LCC models are developed and used by each IM with national data, allowing more detailed cost figures and therefore a higher degree of desegregation of the CBS.

The INNOTRACK cost database will be build using the “high-level” cost (general costs of activities with low desegregation) from each IM participating in LCC modelling tasks (through a questionnaire). As discussed herein, an average and “best practice” cost should be provided, together with a precise description of the boundary conditions linked to each cost element.

As regards the dispersion of the cost data gathered, an homogenization procedure based on the results of LICB (UIC project) is recommended.

Finally regarding the LCC calculation procedure some guidelines have been presented on the application of a probabilistic approach. The probabilistic analysis can be a useful instrument to manage uncertainties on the values of some defined input parameters: RAM parameters (MTBF, MTTR) or unit cost values. The steps to follow are to clearly identify variables with higher degree of uncertainties (and higher impact on LCC) and to build a probability distribution which represents the possible values and their probability (or possibility) of occurrence. The results of a probabilistic LCCA (through Monte-Carlo simulation) is a distribution function with the probability of occurrence of the budgeting parameter considered, generally NPV (Net Present Value) and Annuity Factor, as described in deliverable D6.2.1. This distribution function gives a much more sophisticated and useful tool for decision making, when compared to conventional deterministic analysis plus sensitivity analysis.

The discussion on how to apply probabilistic analysis in railway track LCCA is complemented by an illustrative example.