AUTOMAIN

Augmented Usage of Track by Optimisation of Maintenance, Allocation and Inspection of Railway Networks

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Optimised maintenance activities like, grinding, tamping and other maintenance processes

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The main objective of this report is to deliver results from tasks 4.1 and 4.5 which integrates the results from tasks 4.2, 4.3 and 4.4, amongst them lean analysis of grinding, tamping and maintenance of switches and crossings. The maintenance processes considered in WP1 and WP2 has been mapped against the performance drivers and performance killers (decreases/degrades the performance by decreasing capacity and punctuality), cost and risk drivers. Through elimination/isolation of performance killers, a number of options/innovations have been identified for high performance maintenance and modular infrastructure components and subsystems.

This document is the report covering deliverable D4.2.

Additional information	
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Executive Summary

The deliverable deals with optimised maintenance activities, which considers grinding, tamping and switches and crossings (S&Cs) to fulfil the objective for increasing the capacity of the European rail network to allow increased freight traffic by reducing the maintenance possession time. Link and effect, and optimization models have been conceptually discussed to highlight performance drivers and killers. Maintenance processes for reliable and track design capacity assurance is also discussed.

The concluding remarks of the case study on optimization of grinding are;

- Long enough maintenance windows is necessary to minimise track possession time needed for grinding.
- The use of improved conventional grinding with 64 stones shows that reduction in track possession time in the order of 50 % is possible. This reduction depends on the layout of the track.
- HSG and twin HSG present good opportunity for the reduction of track possession time, in comparison with conventional grinding over 67% reduction in track possession time is possible.
- The grinding cost is in the order of 5 -10 % of the total LCC for the rail and the most significant cost element is the cost of track replacement. This makes decision on time to replace track crucial from LCC perspective.
- An improved conventional grinding machine will have about the same order of cost as the High Speed Grinder, but will most probably give earlier replacement of rail than the High Speed Grinder so the LCC-cost is slightly higher.

For tamping, the outcome of the case study shows that:

- Adequate maintenance window leads to reduced track possession time that will be required on the long run. Around 5 hours would be optimum since the benefit of further increasing the maintenance is very small.
- Optimum possession length is required to reduce the impact of necessary non-value added tasks.
- The behaviour of the track becomes unreliable if the tamping cycle becomes too large or in the absence of one owing to increased number of spot failure with high variation in track possession time.
- Improvement of tamping speed gives the highest reduction in track possession time. 10% improvement in the tamping activities gives 11% reduction in the track possession time while 40% improvement gives about 35% reduction.
- The number of isolated geometry failure over time follows a power law process. Following this, an optimum strategy from track possession point of view is to have a tamping interval of 6 years.

For maintenance of switches and crossings the results found are:

- Value stream mapping together with the simulation that a time saving of 50 % in crossing replacement is possible. However, it requires two welding teams compared to one in current practice.
- In the study on optimal maintenance window in-between regular departures, a maintenance work of 120 minutes was simulated with regular time tables at different frequencies. Results indicates that 40 minutes train frequency could be considered as an optimal window size

regarding train service and maintenance cost. It gives 35 % saving compared to a train frequency of 20 minutes.

These models and simulations can be implemented after suitable modifications as relevant to the IMs for achieving the anticipated 40% maintenance possession time reduction.

1. Introduction

The European Commission funded AUTOMAIN project with the overall objective of increasing the capacity on the European rail network to provide increased freight traffic. This is achieved by reducing the impact of maintenance possessions on the timetable.

Work package (WP) 4 "High Performance Maintenance" consists of five tasks: Identification & documentation of performance killers and drivers, High performance grinding, High performance tamping, Modular switches and crossings, and Optimised maintenance systems/principles, i.e. Tasks 4.1-4.5. WP4 also includes two deliverables. The previous deliverable (D4.1) studied infrastructure managers' (IMs') current railway infrastructure maintenance practice. Findings were collected from WP1 and WP2 as an objective of Task 4.1 and delivered to Tasks 4.2-.4. Besides to look for the current practice of maintenance technologies and procedures, solutions, innovations, possibilities and demonstrators for high performance maintenance and modular infrastructure has been highlighted in D4.1. A description of WP4 is shown in Figure 1. The innovations and options to be examined in this deliverable are high performance grinding, tamping and modular S&C.

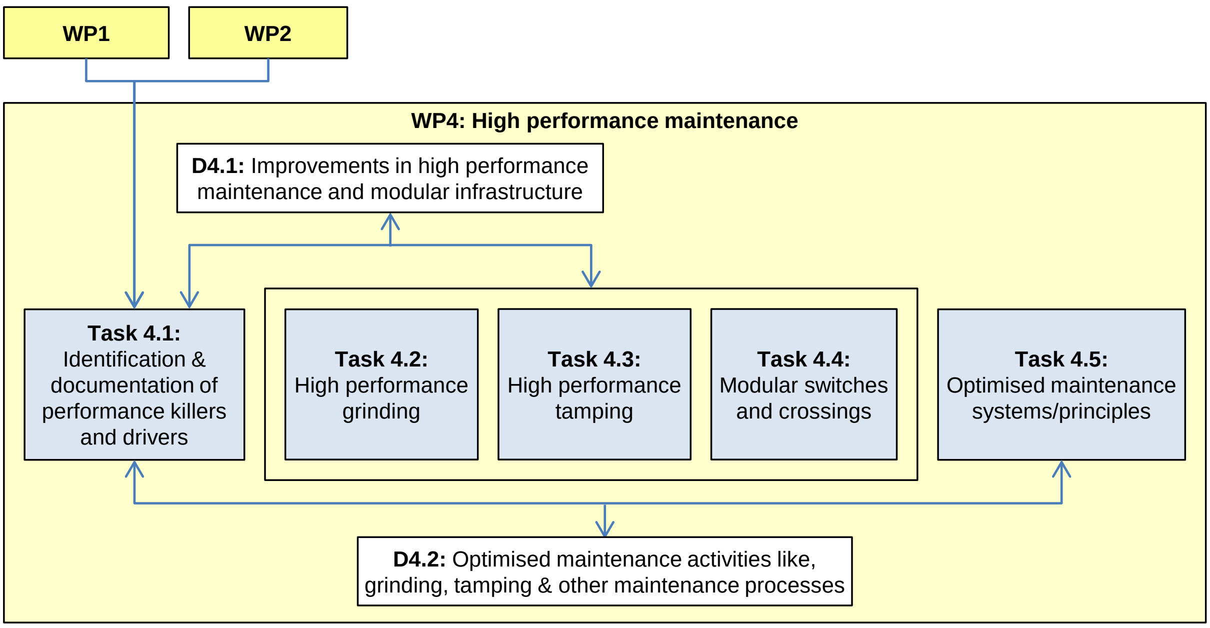


Figure 1: *Description of work package 4 tasks.*

Innovations and demonstrators that have been suggested in D4.1 and D4.2 aim to verify these through optimised maintenance systems/principles. This will provide more availability and capacity utilisation for freight trains.

WP1 and WP2 have provided input concerning current performance drivers (often equal to business objectives, e.g. punctuality, safety, reduced life cycle cost), current Key Performance Indicators (KPI) (e.g. total train kilometer, track quality) and performance killers for tamping. For grinding and modular switches and crossing (S&C), these parameters were identified by using lean process thinking with a method developed by KM&T, including structured observations; value streamed mapping (VSM) and hands off diagrams.

The innovations/options identified in D4.1 are to be verified through link & effect and capacity optimization models. The methods are using optimised principles for implementation by IMs leading to a reliable and track design capacity assurance. The models consider parameters like the type and density of train traffic and other constraints.

This deliverable is looking into the development of link & effect and optimization models to identify the most optimal maintenance approach for railway infrastructure. Development and verification is undertaken on the basis of life cycle costing (LCC) and RAMS (reliability, availability, maintainability and safety).

The overall goal and objectives of AUTOMAIN and interdependencies are further shown in Figure 2.

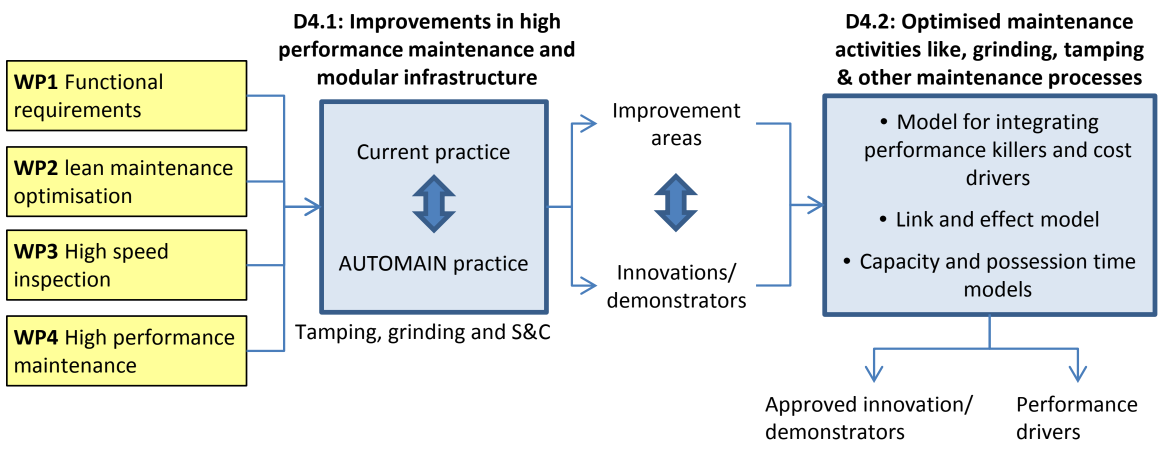


Figure 2: *The interdependencies between the different work packages*

2. Maintenance improvement for capacity increase

For improvement analysis, it is vital to measure and monitor the asset management process for railway infrastructure, see Figure 3. RAMS (Reliability, Availability, Maintainability and Safety) and LCC (Life Cycle Cost) methodology are two acknowledged methods for assisting the optimisation process. Key Performance Indicators (KPIs) and categories of performance killers/drivers for RAMS and LCC needs to be identified, developed and transformed into a railway user environment for adaption and implementation.

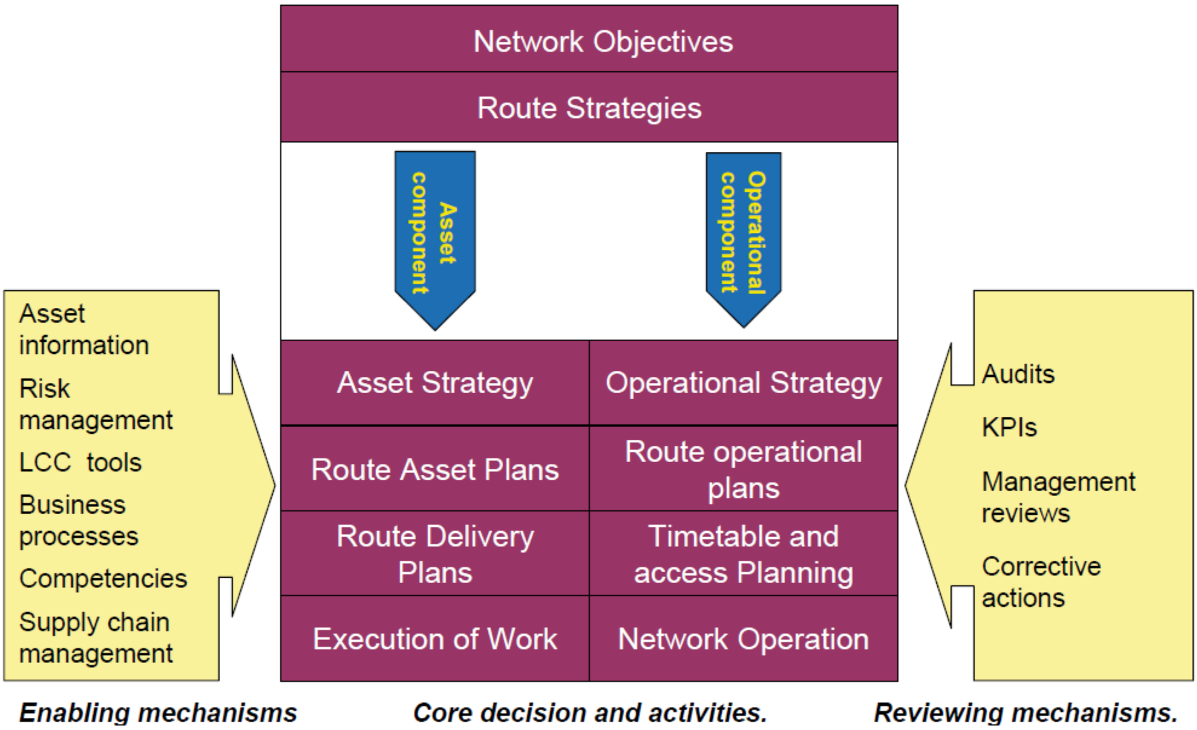


Figure 3: Optimisation process of railway assets with KPIs, LCC and risk (UIC 2010).

Earlier findings from INNOTRACK project shows that LCC and RAMS are in an initial state of use in the railway transport industry. More and more studies are undertaken by various transport industries and academies to apply RAMS and LCC approaches through KPIs for achieving high performance maintenance.

WP1 has provided a set of functional requirements, a performance framework for the project which is used to evaluate the impact on infrastructure managers' performance of the final results.

WP1 has also conducted a benchmarking of asset management (AM) strategies, policies and performance and how the individual infrastructure managers (IMs) in Europe translate their company goals (such as punctuality) to AM strategies. A high level review of rail infrastructure maintenance and inspection processes within the European railway infrastructure maintenance organisations was created to allow comparisons with approaches used in other industries (e.g. highways and aerospace).

The following activities have been identified under D2.1, and Task 4.1 for optimizing maintenance activities to provide more capacity, which are discussed subsequently in this deliverables:

- High performance grinding
- High performance tamping
- Modular S&Cs
- Optimized link and effect, and maintenance optimization models

For measuring the effect of the innovations on the possession time, the following KPI's were considered:

- The length of the train free period needed for the maintenance activity
- The length of each sub activity within the train free period
- The frequency of the activity (number of activities per year).

2.1 RAMS

For finding needs and identifying improvements areas for capacity increase for the IMs, the EN50126 standard (Railway applications of reliability, availability, maintainability and safety) and similar standard procedure for dependability management are followed. The goal of a railway system is to safely achieve a defined level of rail traffic in a given time, and this level of service could either be qualitative (quality of delivered traffic) or quantitative (amount of traffic). These two performance measures are connected to the technical performance of the railway system. The technical performance of railway infrastructure is described as its RAMS characteristics. RAMS describes in qualitative and quantitative terms the degree that a system, or the sub-systems and components comprising that system, can be relied upon to function as specified and to be available and safe. As shown in Figure 4, railway RAMS together with other attributes contributes to the quality of railway service and also the capacity utilisation. Railway RAMS has a clear influence on the quality with which the service is delivered to the customer.

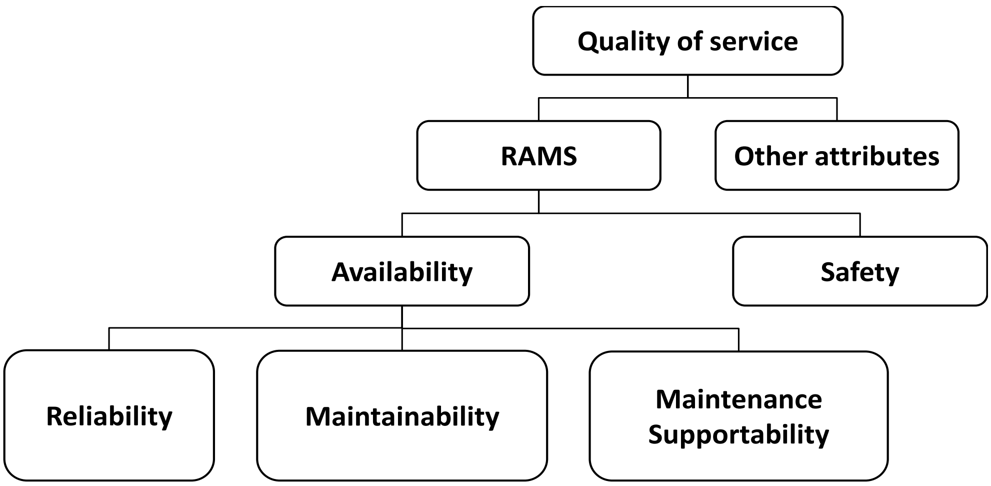


Figure 4: Railway RAMS as adapted from (CEN 1999, Misra 2008)

The elements of railway RAMS as presented in Figure 4 differs from the standard EN 50126, as this modification is made to clearly show the concept of availability and its relationship with the influencing factors. The additional element of maintenance supportability is considered to be essential to maintain the system at the specified availability level within the required life cycle cost. The description in Figure 4 is also in line with EN 13306:2010 “Maintenance terminology”.

Relevant analysis and models have considered the above mentioned parameters and used for the elimination or isolation of performance killers, and also control or elimination of cost and risk drivers to provide more capacity for freight trains. With inputs from WP1, 2 and Tasks 4.1, 4.2 and 4.3, the performance killers and drivers are defined, identified and further investigated for appropriate measures in form of innovation or optimization using models.

2.2 Definitions of performance killers and drivers

Performance killers and drivers are described as factors of poor or good performance, respectively. Under AUTOMAIN project, the concept of performance killers and drivers are used for identification and implementation of these parameters to achieve improved capacity utilisation for the IMs. The concept of performance killers and drivers in a maintenance performance measurement (MPM) system is shown in Figure 5. The performance killer and drivers are defined as under:

> *A performance killer is an input element to a process or organization, which hinders and results in poor performance of the process or business.*
>
> *A performance driver is a supporting input element to a process or organization, which drives and enhances the performance of the process or business.*

Thus, a cost driver is a tangible input element to a process, which drives and affects the costs. Thus, a performance killer is similar to cost driver, but more intangible, since it does not directly affect the costs, e.g. inappropriate tools and methods.

Another definition of performance killers are: factors that reduces performance without being strong enough to stop the process, e.g. bottlenecks in capacity; lack of proper tools and facilities; faulty procedures; inadequate information/communication flow, non-availability of resources; etc. In other words, a performance killer can be non-availability of resources. Further discussion on terminology can be found in Stenström et al. (2013).

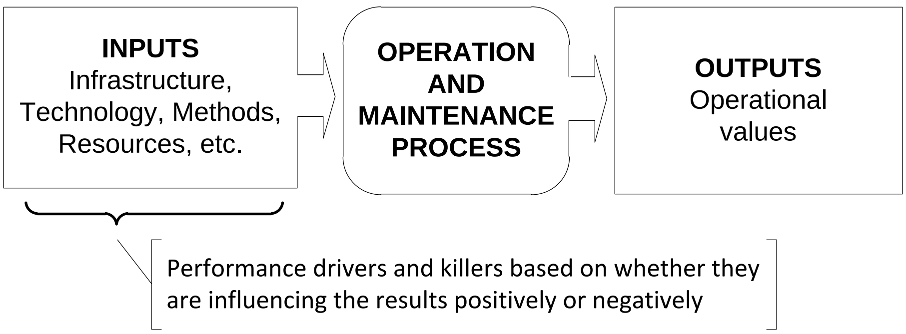


Figure 5: Concept of performance killers and drivers.

2.3 Result of improvements analysis for high performance maintenance and modular switches and crossings

The result from WP1 shows that only some Infrastructure Managers (IMs) differentiates their KPIs according to the type of infrastructure or railway line and existing mechanisms. The measurement of performance varies considerably between IMs and not all IMs are able to link the performed maintenance activities with track access periods through the maintenance data management system. This means that there is a lack of measurement's for high performance maintenance and that current measurements cannot be used to describe or find options for improvements in the current maintenance process, that can provide less maintenance time in the current time table, break down the maintenance in big chunks or split down the work in small blocks that fit within the planned time table.

The lean analyses of the current process for tamping, grinding and modular infrastructure proved worthwhile and there were a number of interesting differences noted between IMs as well as a good number of common issues. It was difficult and time consuming to arrange observations for directly comparable shifts across the railway administrations. Major differences were recognized amongst the IMs concerning strategies in use, amount of action taken, density of traffic, funding and possible resources allocated. It was therefore decided to use the results only to identify areas for improvement in the maintenances process. The main improvement areas are: planning of maintenances activities, low utilization of possession time, standard operating procedures, data capture, training and communication.

Moreover, to use the lean approach for future internal benchmarking or for benchmarking different IMs, there is a need for harmonization/normalization of KPIs and performance drivers to find the best practice and improvement areas.

2.3.1 Analysis of performance killers of tamping, grinding and S&Cs

The inputs from WP1, WP2 and key concerns from the lean analysis (see the column *Issue* in Tables 1-3), are considered under WP4 for performance killers. The performance killers are considered and analyzed for their relationship with the improvements, innovation and best practice (see the column *Improvements* in Tables 1-3 and Chapter 3 in D4.1), categorization, issues and possibilities of usage/application. The performance killers are further discussed in this deliverable to connect them to KPIs. See Tables 1-3 and Section 2.4. The most important, with high potential to implement and highest priority issues with their KPIs are considered for grinding, tamping and modular switches and crossings. For details see Appendix B.

Table 1: Performance killers of grinding with the high priority (see Appendix 1).

Issue	Category	Possibilities	Improvements (Based on Chapter 3 in D4.1)	PI
Grinding debris/slag collectors (manual) are generally slower than the grinding machine, resulting in delays and reduced productivity	Active possession time	-Implement automatic collectors	Automated slag collectors	Measureable through KPI_3 (D1.2) Debris collection efficiency (collection speed/ grinding speed)
Insufficient central knowledge about specific track locations resulting in sub-optimum maintenance plans and / or safety plans. Experienced by most of the IMs.	Logistics and schedule	-Improve techniques for localization, e.g. improve integration of GPS and local systems -Improve software for correlation of data and positioning with use of track curvatures and original track structure data	AUTOMAIN database/software Development of a robust system which integrates inspection data, maintenance data and other relevant location data (e-maintenance).	Not measureable through KPI_3 (D1.2) Average positioning accuracy
Maintenance activities are often given low priority by traffic control centre (TCC), and there is a lack of follow-up or consequences where delays are caused to maintenance due to issues with late running train services	Possession time planning	-Planning software for more automated train control -Better communication between train operator/TCC and maintenance department -See best practice in EU project "ONTIME"	Improvement in train planning and control system system/protocols. Standard Operating Procedures	Not measureable through KPI_3 (D1.2) • Work backlog $\left(\frac{\text{Actual maintenance time}}{\text{Planned maintenance time}}\right)$

Table 2: Performance killers of tamping with the highest priority of 9 (See Appendix 1).

Issue	Category	Possibilities	Improvements (Based on Chapter 3 in D4.1)	PI
Low utilisation of possession time, and often a low level of confidence which prompts high levels of contingency time to be planned in	-Possession time planning -Logistic & Scheduling	• Plan optimum production depends lifting height and insertions • Improved planning software	Improved maintenance organisation (soft parameter) Standard Operating Procedures	Measureable through KPI_3 (D1.2) Maintenance efficiency e.g. $\left(\frac{\text{Track length tamped}}{\text{Mainetenance window}}\right)$ $\left(\frac{\text{Actual track length tamped}}{\text{Planned track length}}\right)$
The time spent waiting for the machine to warm up	Resources planning	• Start machine 1 hour before possession and do input and safety instruction etc.	Technical innovations - automated tamping machine (Hard parameters)	Measureable through KPI_3 (D1.2) $\left(\frac{\text{Waiting time}}{\text{Mainetenance window}}\right)$
Distance between the machine stabling point and the worksite, e.g. sidings every 20 km ≈ 15 min	Logistic & Scheduling	• Two-way vehicles (rail and road vehicle), however low capacity machines at present • Develop a software for better logistic support • Develop vehicle with reversible plate together with perpendicular siding	• Design track for Maintenance • 2 way vehicles, future innovation (Hard parameters)	Measureable through KPI_3 (D1.2) Maintenance supportability: $\left(\frac{\text{Transportation time}}{\text{Mainetenance window}}\right)$

Low knowledge of degradation, it is unclear how far track should be allowed to deteriorate and what limit should trigger a special maintenance activity. 3,8. There is insufficient understanding of the optimum point at which to plan intervention	• Maintenance requirements • Resources	• See standards EN 13231 EN 13848(1-6) and EN 15341 • Learning from best practice IHHA, INNOTRACK, etc. • Proper understanding of degradation is key, in UK LADs being developed and implemented to provide this information • Prognostic tamping performed at DB • Improve threshold values and integrate with root causes for line classes • Optimise tamping strategy	AUTOMAIN maintenance stratgy Improved strategy using models (Hard parameter)	Not measureable through KPI_3 (D1.2) • Track quality Index (TQI) and order in quality classes Track quality index • Recovery at intervention
Lack of standardisation regarding key tamping parameters such as the optimum speed of tamping, the pressure to be applied to the tamping tines and tine depth. There is a need for better guidance on the optimum approach.	Resource planning tool	• Better training • Improve objectives, maintenance limits and indicators within the tamping strategy	• Training of operators • Design of tamping machine with automatic setting of tamping parameters	Not measureable through KPI_3 (D1.2) Tamping efficiency (function of operator)
Inadequate tools for analysing of existing track recording data to trend deterioration rate	• Logistic & Scheduling • Possession time planning	• Develop software, especially geographical localization and user friendliness • Training • International cooperation for sharing best practices	AUTOMAIN database/software New software	Not measureable through KPI_3 (D1.2) Use of survey with rating scale, e.g. scale of 1-5

Machine safety checks and briefings should be undertaken prior to arriving at site if at all possible	Maintenance requirements	• Start machine 1 hour before possession and do input and safety instruction etc.	AUTOMAIN database/software Development of new software or integration of existing maintenance and signal system	Measureable through KPI_3 (D1.2) $\left(\frac{\text{Preparation time}}{\text{Mainetenance window}}\right)$

Table 3: Performance killers of S&Cs (Task 4.4).

Issue	Category	Possibilities/Improvements	PI
Active repair time is commonly long for rail components in S&Cs	Active possession time	• Earlier failure detection for early planning • Modular items for faster maintenance • Panel Replacement	Measureable through KPI_3 (D1.2) • Maintainability- Design modular S&Cs (mean active repair time) • Administrative delay • Logistic delay
Work cannot be done in the given time frame Very tight time constraints leave little margin for error and/or rework.	Planning	• Increase the skills of the inspectors • Welder should make site visit in an early stage of the planning process • Training of personnel and development of standard operating procedures	Measureable through KPI_3 (D1.2) Percentage of work orders performed within planned time
If the inspection result of finished work is outside of standard the fault will have to be reworked	Execution Repair / Built up welding	• Replace crossing and repair it in workshop • Implement a replacement strategy (Modular concept) instead of repair and built up welding in track	No. of backlogs
During frozen conditions ice can fall from passing high speed trains very close to where the crew is working Working environment can be unsafe when grinding due to dust and fumes	Safety	• Work inside maintenance shed • Dust suction or mouth protection equipment provisioning	No. of incidents/accidents related to S&C
Today we use possession time for inspection of S&C	Planning	• On-line measurements through an overhead camera connected on-line with a computer • Use trains with video inspection	Measureable through KPI_3 (D1.2) • Time needed for inspection of video • Possession time used for inspections

Degradation rate of S&C is still high after replacement of a component, i.e. the root cause of the failure is still there	Infra	• Implement panel replacement as a new strategy	Not measureable through KPI_3 (D1.2) • No. of failures • Degradation rate • MTBM • Maintenance time
The length of spare rail parts is often too short when the old one has been cut out of track. Marking is not always done which can result in having the wrong amount of rail in track	Infra	• Implement the possibility of ordering of extended rail spare parts • Implement procedure for measuring rail part lengths in the planning process	Not measureable through KPI_3 (D1.2)
Possessions can be rejected if the time is longer than the train operator can allow (when ordering 4-12 weeks before maintenance), e.g. 2x4 hours.	Planning	Early failure detection	Not measureable through KPI_3 (D1.2) No. of late possessions requested
No standard procedures exist for temporary repairs	Planning	Make standard operating procedure for temporary repairs	Not measureable through KPI_3 (D1.2)
Non-standard S&Cs models have long delivery times Bended S&C components requires longer delivery times (longer to manufacture)	Planning & logistic	• Keep non-standard material in stock • Develop strategy for handling old critical spare parts	Not measureable through KPI_3 (D1.2) No. of out-of-stock

2.4 Link and effect model

The link and effect model is a methodology for developing performance measurements systems, by combining performance measurement and engineering principles for proactive management of physical assets (Stenström et al. 2013). The model is built on continues improvement for dynamic performance measurement to meet changes in business objectives (Bourne et al. 2002):

- Change in business goals, objectives, strategy, policies, etc.
- Change in technology and communication, e.g. maintenance procedures and ERP
- Organisational changes
- Evolving regulations, e.g. health, safety, security and environment
- Stakeholder requirements
- Fluctuations in economy, i.e. the business cycle
- Changes in physical assets

The model is also constructed as a top-down and bottom-up approach to meet issues in performance measurement like:

- Strategic planning not linked
- Poorly defined indicators
- Too many key indicators
- Problem of turning data into information
- Striving for perfection
- Time and expense
- Culture, resistance to change and consequences of measurement

Many improvement methods have its basis in a continues improvement process, like the plan-do-study-act (PDSA) cycle, also known as the Deming cycle, Shewhart cycle or Kaizen cycle (Imai 1986). Furthermore, it has been found that organisations use the key elements, or components, of strategic planning differently, e.g. vision, mission, goals, objectives, etc. (Stenström 2012). The link and effect model is therefore based on the PDSA cycle (plan-do-study-act) with emphasise on the key elements of strategic planning. The model has two main components: a four-step continuous improvement process and a top-down and bottom-up approach; see *Figure 6*. The methodology starts by breaking down the objectives, followed by updating the measurement system accordingly, analysis of data and finally identification and implementation of improvements. The model is preferably used on a yearly cycle as the IMs' objectives commonly changes with annual appropriation letters.

The first step of the link and effect model concentrates on the strategic planning, which also include gathering stakeholders' objectives (usually conflicting) and assembling them into a common framework. For railways in the EU, aligning and harmonisation start at the European level and are broken down to national governmental and infrastructure manager levels, i.e. from strategic to operational planning.

Strategic planning can be described as the process of specifying objectives, generating strategies, and evaluating and monitor results (Armstrong 1982). The terminology of strategic planning can vary between organisations and researchers; see discussion in the case study. Therefore, key elements, or components, of strategic planning are given in Table 5 to assist in Step 1 of the link and effect model.

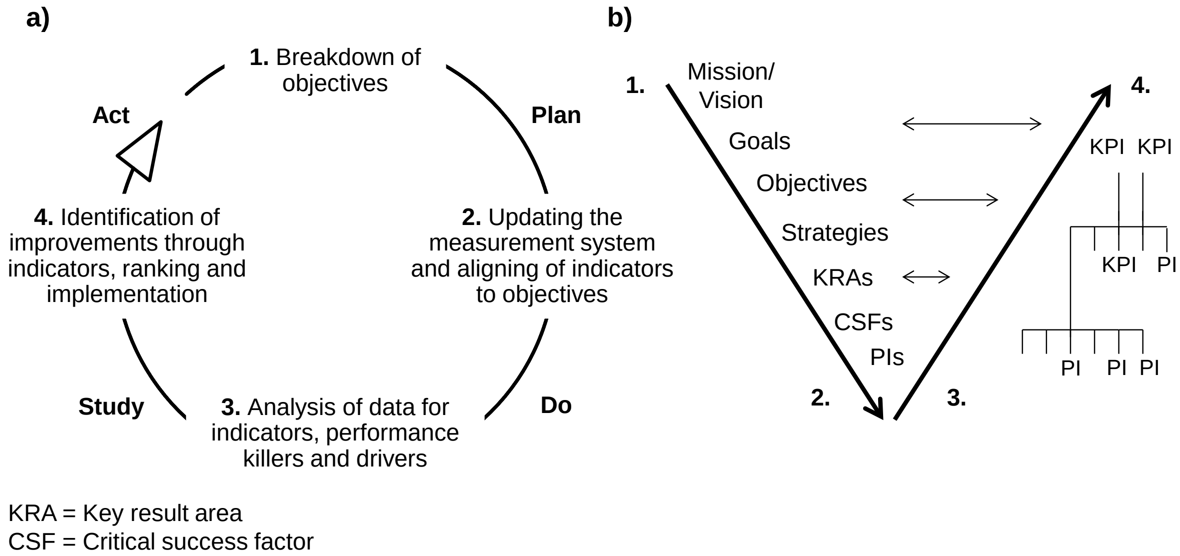


Figure 6: The link and effect model with a one year cycle time, based on (a) a four steps continuous improvement process and (b) a top-down and bottom-up process. The numbers in (b) represents the steps in (a).

Table 4: Key elements of strategic planning *(Stenström et al. 2013)*.

Term	**Description**
Vision statement	A statement of what an organisation hopes to be like and to accomplish in the future (U.S. Dept of Energy 1993).
Mission statement	A statement describing the key functions of an organisation (U.S. Dept of Energy 1993). Note: vision and mission are set on the same hierarchical level, since either can come first, e.g. an authority has a vision, and gives a mission to start a business; the business can develop its own vision later on
Goals	A goal is what an individual or organisation is trying to accomplish (Locke et al. 1981). Goals are commonly broad, measurable, aims that support the accomplishment of the mission (Gates 2010).
Objectives	Translation of ultimate objectives (goals) to specific measureable objectives (Armstrong 1982), or targets assigned for the activities (CEN 2011), or specific, quantifiable, lower-level targets that indicate accomplishment of a goal (Gates 2010).
Strategy	Courses of action that will lead in the direction of achieving objectives (U.S. Dept of Energy 1993).
Key result areas (KRAs)	Areas where results are visualised (Boston et al. 1997), e.g. maintenance.
Critical success factors (CSFs)	Are those characteristics, conditions, or variables that when properly managed can have a significant impact on the success of an organisation (Leidecker et al. 1984), e.g. high availability. CSFs can be on several levels, e.g. organisational and departmental.
Performance indicators (PIs)	Parameters (measurable factor) useful for determining the degree to which an organisation has achieved its goals (U.S. Dept of Energy 1993), or numerical or quantitative indicators that show how well each objective is being met (Pritchard et al. 1990).
Key performance indicators (KPIs)	The actual indicators used to quantitatively assess performance against the CSFs (Sinclair et al. 1995). A KPI is a PI of special importance comprising an individual or aggregated measure.

The performance measurement system of organisations is under constant pressure from strategic planning, organisational changes, new technologies and changes in physical asset structure. Therefore, Step 2 in the link and effect model concerns updating the measurement system according to new stakeholder demands and objectives. See *Figure 7*.

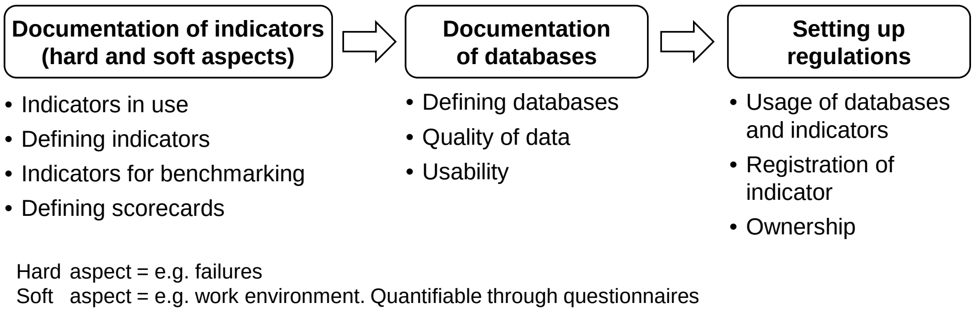


Figure 7: Key requirements for performance measurements.

A good performance measurement system does not necessarily require a high level of precision; it is more important to know the indicators trend movements, i.e. how the current value compares to historical values (Kaydos 1991). As a result of new and better ways of measuring, changed objectives, or due to organisational changes, the way that indicators are measured or calculated can be changed. It should be noticed that the trend movement can be lost, and therefore the old ways of calculating should be kept and presented with the new ways of calculating for a period of time, i.e. overlapping (Stenström 2012). Some indicators can give a good record for trend studies quite fast, while others need several years to be trustworthy.

Organisations collect vast amount of data, but turning the data into information is often lacking (Davenport et al. 2001, Karim et al. 2009). Accordingly, analysis methodologies are developed in Step 3 by use of various statistical methods, for construction of performance indicators and identification of performance killer and drivers. Since data collection cost resources, another important aspect in Step 3 is to identify what data is required and what data is superfluous.

Aggregation of data is a weakness of traditional performance measurement systems since it can make the indicators abstract as the underlying factors can be unknown (Stenström 2012, Stenström et al. 2012), e.g. total train delay or total number of failures. Therefore, the link and effect model complements thresholds with the underlying factors responsible for the performance. Indicators with thresholds are commonly given attention when some limit has been passed, making them reactive in nature. In contrast, the link and effect model gives the underlying performance drivers and killers, providing a starting point for improvements, i.e. more of a white box approach. See *Figure 8*.

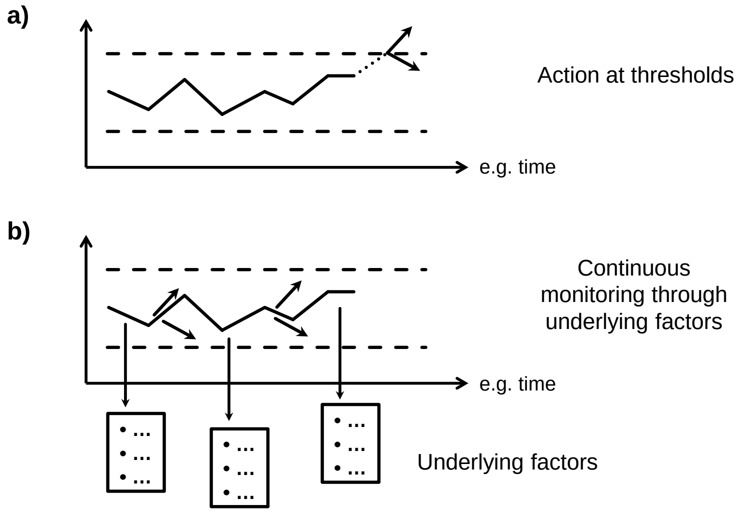


Figure 8: (a) Traditional performance measurement system with thresholds. (b) Link and effect model complementing with the underlying factors of the indicator.

The link and effect model utilises continuous improvement with the ultimate goal of facilitating decision-making, by providing an up-to-date performance measurement system. Step 4 includes therefore simulation, ranking, reengineering physical assets and processes, implementing prognostic techniques and further defining indicators and databases.

2.4.1 Applying the link and effect model on AUTOMAIN

The link and effect model is developed to support infrastructure mangers in the operation and maintenance of railways. The model is applied to the AUTOMAIN project to facilitate the improvement and result measurement within the project.

Step 1: Breakdown of objectives

The breakdown of objectives according the findings in Section 2.3 and AUTOMAIN "Description of work" is shown in *Figure 9*.

Step 2: Updating the measurement system and aligning of indicators to objectives

The second step of the link and effect model is partly answered by *Figure 9*. Relevant KPIs are:

KPI_3 = (1 – total possession time required for maintenance using innovative techniques / actual required possession time for maintenance) x 100 %

KPI_4 = (1 - possession time required after using modular elements/ actual required possession time) x100 %

Further breakdown of the KPIs related to possession time gives the following parameters for grinding, tamping and S&Cs:

- Transportation time
- Non-value adding time (t_{NVA})
    - Preparation, confirmation, communication, waiting and lost time

- Active maintenance time (t_{Active})

Aim/vision:	Reduce track possession time of inspection and maintenance with around 40 %
Innovations:	2. Higher performance infrastructure inspections 3. Higher performance track maintenance 4. Modular infrastructure components and subsystems
Functional and capability requirements:	**01:** To be able to collect performance and condition data using automated methods **05 and 10:** To be able to reduce the necessary time for activities (TTR/TTM) and access work sites rapidly – Reduce transportation time, non-value adding time (preparation, confirmation, communication, waiting and lost time) and active time with 40 % **13:** To be able to plan on the basis of very low levels of reactive maintenance **15:** To be able to have very low track renewal frequency **22:** To be able to have instant access to processed data results **23:** To be able to have new switch and crossing designs with far fewer discontinuities **30:** To be able to embed knowledge and decision rules in the design of objects and their control systems
Strategy:	Lean analysis, value stream mapping (VSM) and optimisation models
Key result areas (KRAs):	Grinding Tamping S&Cs
Critical success factors (CSFs):	• Improve planning process of grinding, tamping and S&Cs • Increase speed of grinding, tamping and S&Cs activities • Automate data collection, analysis and presentation of data • Optimize strategy for grinding, tamping and S&Cs
Key performance indicators (KPIs):	**KPI_3** = (1 – total possession time required for maintenance using innovative techniques / actual required possession time for maintenance) x 100 % **KPI_4** = (1 - possession time required after using modular elements/ actual required possession time) x100 %

Figure 9: Breakdown of AUTOMAIN objectives according to the link and effect model.

Step 3: Analysis of data for indicators, performance killers and drivers

Analysis has been carried out in previous deliverables, as well as in this deliverable, through lean analysis, value stream mapping and optimisation modelling. The analysis is found in Chapters 2-4.

Step 4: Identification of improvements through indicators, ranking and implementation

The optimization models in Chapters 2-4 together with other innovations and demonstrators, answer to KPI_3 and KPI_4. The identification of improvements and results are concluded in Chapter 5, which is part of Step 4 of the link and effect model.

2.5 Maintenance processes for reliable and track design capacity assurance

An aspect of railway infrastructure management which is promising for the enhancement of existing infrastructure capacity is the improvement of maintenance process. Maintenance process is the course of action and series of stages to follow in order to define appropriate strategy and implement the same. Maintenance process is capable of supporting a reliable track capacity and also increases the present capacity of existing railway infrastructure. Efficient and effective maintenance process including setting of objectives, strategy formulation, planning & scheduling, execution, assessment and improvement are essential requirement for capacity assurance.

In developing a maintenance programme which adequately addresses both track possession time and also quality of maintenance work it is necessary to have a total perspective of the system and different improvement aspects as shown in Figure 10. The technical performance of railway system depends on its present condition which in turn is a result of so many interacting factors highlighted in *Figure 10*. The factors can be broadly categorized into four groups

1. Infrastructure condition: Basically defined by its initial quality
2. Operating condition: It is defined by its operation profile, procedure and logistics
3. Maintenance condition: Defined by maintenance process and its philosophy.
4. Boundary conditions: Incidences and factors which are mandatory protocols, human influence or uncontrollable factors, such as weather.

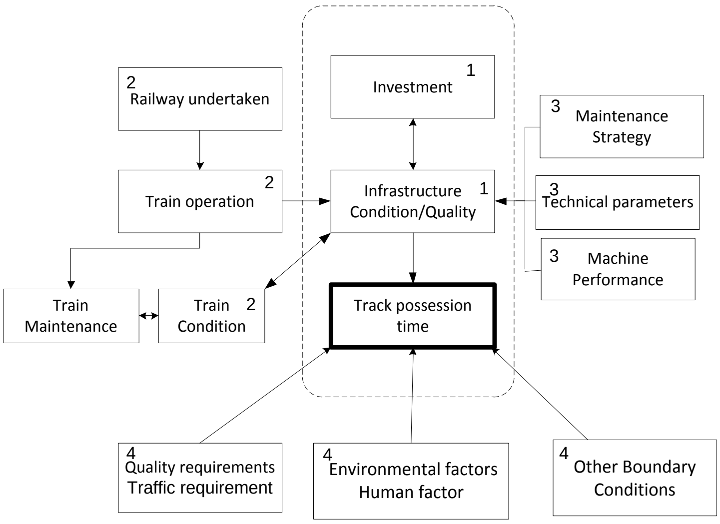


Figure 10: Aspects of capacity assurance

2.5.1 Infrastructure condition

This is sometimes referred to as system condition or technical characteristics at the installation of the asset. The quality characteristics could either be of conformance of the performance depending on parameter in consideration. It is dependent on the investment strategy and it has a huge effect on the behaviour of a system during its life cycle. A major challenge in life cycle management of railway infrastructure is the question of initial quality and maintenance efforts needed to satisfy a specific functional and traffic requirement of railway applications. It has been established that maintenance of a complex system such as track structure cannot restore its initial quality. This therefore underscores the significant contribution of initial system condition to maintenance need and consequent track possession time. The basic requirement of effective maintenance process is to install new track to the best initial quality; to provide the best and most durable track geometry possible requiring minimum maintenance and track possession time.

The initial system condition needed for optimum quality, durable quality and reduced track possession time is expected to consider the following

1. Good track layout design
    - Location of critical systems such as S&C, level crossing, bridges, tunnels, viaducts etc.
    - Form and position of transitions
    - Design and location of curves
2. Rail characteristics
   These include appropriate rail profile, rail grade, type, rail surface and other relevant characteristics of the rail. For example the rail surface must be uniform and free of surface or subsurface irregularities such as corrugations, which can induce dynamic load variation on the track components, subsequently affecting the ballast and substructure. Such initial rail unfitness accelerates track deterioration and increase track possession requirement.

3. Substructure
   Adequate geotechnical properties of the substructure at installation provide solid support for the track structure and as such extend time between maintenance interventions. Homogeneous substructure gives uniform resistance to loading condition and keeps the track structure in position as much as possible while contributing to ballast memory prevention and to achieve track stiffness targets.

4. Ballast quality
   The rock properties, size, shape and cross section of the installed ballast must be suitable for railway application and functional requirement specific for the traffic. It must give room for drainage and also interlock with surrounding members for load distribution without breaking down under traffic load or maintenance regime. The initial size distribution is a quality measure whose conformance should be checked at installation to minimize need for maintenance during the life of a track structure.

5. Drainage
   Another quality aspect which contributes positively to the technical condition and maintenance need of track structure is drainage. This construction in form of ditches, ballast drainage, subgrade drainage systems support the channelling of surface water and run offs away from the track to keep proper resiliency under the sleeper and other points. This helps to keep the geometry quality of the track and reduce the need for frequent intervention during the life of the infrastructure. This extends the length of life of the track.

2.5.2. Maintenance Parameter

Maintenance is well defined as the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function. All maintenance actions especially the large scale maintenance which are mechanical and systematic have unique operational parameters that determines the performance of the maintenance in terms of durability, efficiency, quality, and also deterioration afterwards. The condition and performance of the track structure is outcome of the mix of the operational parameters of the mechanized function. This inevitable have direct or indirect influence on the maintenance track possession time during the life of the asset. A balance mix of operational parameters is essential to achieve a reliable and design track capacity. Some essential tamping and grinding parameters, as determined from task 4.1, 4.2 and 4.3 are given in Table 5.

Table 5: Maintenance parameter to achieve reliable track capacity

Tamping parameter	Grinding parameter
Tamping tine depth	Stone quality or grade
Tamping squeeze pressure	Rotation speed
Tamping squeeze time	Machine grinding speed
Design overlift	Stone pressure
Longitudinal position of tines	Stone angle and position
Lateral position of tines	Facet width
Tamping tine wear and type	Number of passages
Minimum track lift	Number of stones
Maximum track lift	
Double tamping of sleepers	
Working method (Relative or Absolute)	

2.5.3. Machine Performance

The achieved capacity on a network depends on required track possession time for planned maintenance and also incidental track possession time for unplanned track outages. Besides the implemented maintenance strategies and technical aspect related to the state of the track structure, maintenance possession time depend on the performance of the maintenance machine available to execute the maintenance work. The main objective of any capacity assurance program (CAP) for a railway network is to ensure that the designed and planned network capacity is achieved. Such assurance program describes the activities necessary to fulfil the objectives, how they will be carried out, by whom, and when.

The performance of maintenance machine is a key element to be taken care of in capacity assurance programme as far as maintenance is concerned. The overall performance of heavy machines such as those used for tamping and grinding activities is a function of both capacity performance and dependability (see Figure 11).

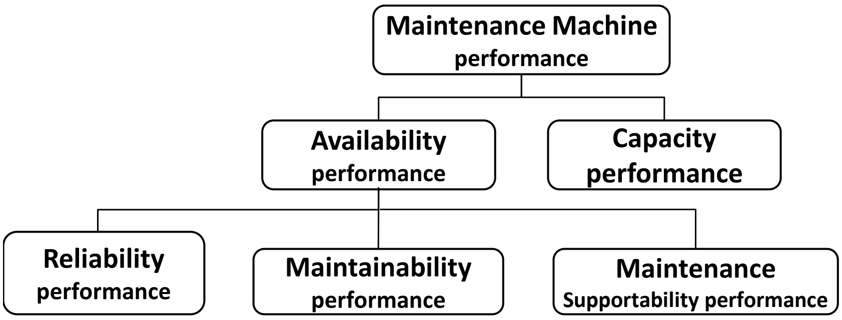


Figure 11: Maintenance machine performance

Capacity performance is a measure of the ability of an item to meet a service demand of given quantitative characteristics under given internal conditions (IEC 1990). The ability of a maintenance machine to deliver or function according to design capacity and/or current demands is referred to as its capacity performance. This is constrained by the structural decision made early phase of the life cycle of the machine. The definition of the system and application conditions, apportioned system requirements and other design considerations determine the capability and consequent capacity performance of maintenance machine. In relation to track possession time which is the subject of AUTOMAIN, relevant indicators of capacity performance of tamping and grinding machines are: travelling Speed, working speed, quality of work (also see table 1-3). The capability and production indicators of some common tamping machines and grinding machines used by some IMs are given in Figure 12-14

Line Tamper					
	Lift	0-30mm	30-60mm	60-80mm	
Type	Sleepers	1x	2x	3x	Insertations
09-16	1x	800	600	300	m/h
09-32	2x	1100	800	400	m/h
09-3x	3x	1500	1100	800	m/h
09-4x	4x	2000	1600	1300	m/h
Normal sleeper distance = 580-620mm					

Figure 12: Performance indicator of a line tamper

Universal (Both Line and Switch Tamper)					
	Lift	0-30mm	30-60mm	60-80mm	
Type	Sleepers	1x	2x	3x	Insertations
Unimat 08-475-4S	1x	500	300	150	m/h
Unimat 09-16-4S	1x	800	600	300	m/h
Unimat 09-32-4S	2x	1100	800	400	m/h
Normal sleeper distance = 600mm					

Figure 13: Performance indicator of a Universal tamper
(Production in Switch differs; it depends on the lift, type of switch and other relevant parameter)

Universal (Both Line and Switch Grinder)				
	Speed (up to) km/h			
Type	Transport	Grinding	Length	No stones
Loram RG400	100	32	152-213	60-150
Speno RR48	100	12	113	48
Speno RR16	80	12	31	16
Vossloh HSG	120	80	94	96

Figure 14: Performance indicator of some line grinder[1]

On the other hand the dependability of tamper and grinder is a principal factor that determines their delivery, performance and eventual track possession time. Dependability refers to the collective term used to describe the availability performance and its influencing factors: reliability performance, maintainability performance and maintenance support performance. Availability performance is "the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided (IEC 1990). A common problem with maintenance machines is lower operational availability when compared to either inherent availability or planned availability. This informs the implementation of availability improvement programme in order to enhance the overall machine maintenance and usage factor. The output of availability improvement programme will be a proposed continuous improvement plan that consists of prioritized actions designed to achieve machine performance close to the inherent availability performance. The programme consists of the following operations (Barabady et al. 2010):

1. Data collection
2. Modelling and data analysis
3. Creation of different alternatives for improvement
4. Decision making

[1] ww.speno.org, www.loram.com and http://www.vossloh-rail-services.com/en/products_services/high_speed_grinding/high_speed_grinding.html

2.5.4. Maintenance Strategy

Achieving a reliable track in terms of technical performance and also meeting the designed capacity of a network requires decision support tool to optimize maintenance plan and schedule. This is even of high importance in the case of large scale maintenance activities such as grinding, tamping or switches and crossing maintenance. Maintenance of systems or units after failure may be costly, and sometimes requires an extended track possession time to restore it to a working state. This gives rise to an important maintenance concern of why how, when and to carry out maintenance including the problem of which unit of railway infrastructure should be maintained preventively before failure. However, it is not wise to maintain units with unnecessary frequency because this is neither economical nor effective practice to ensure design capacity. From this viewpoint, the optimised maintenance strategy will consider preventive restoration at specified interval or based on prognosis and corrective restoration in appropriate instances.

In developing an optimum maintenance strategy to assure track design capacity or reduce track possession time, the following aspects must be considered in the modelling procedure: layout of the system, applicable maintenance policy, possible maintenance level, desirable optimization criteria, planning horizon, amount of system information and appropriate model tool. Figure 15 shows essential aspects that should be accommodated in a reliable maintenance optimization model.

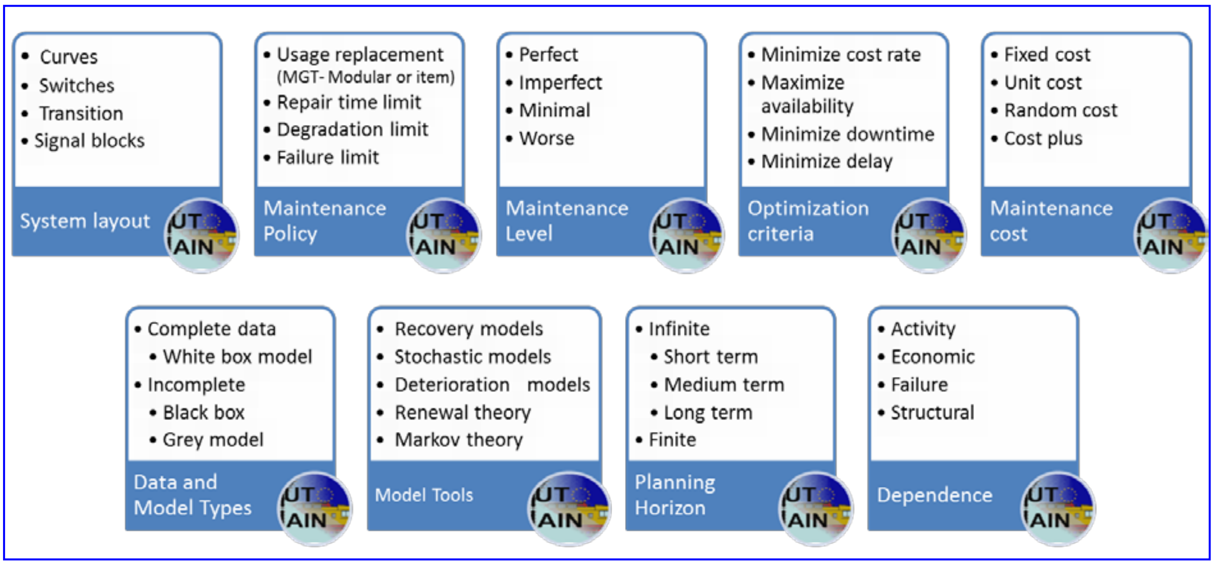


Figure 15: Essential considerations for railway infrastructure maintenance optimization. Adapted from (Wang et al. 2006).

3. Optimized models and decision support tools for grinding

The management of maintenance process requires appropriate strategy and optimized model in order to achieve maintenance excellence. Optimization is a process that seeks optimal solution and makes compromises to achieve what is most important. In maintenance optimization, a balanced mix of cost, risk and performance is often sought after. An optimum maintenance solution seeks for the input into maintenance that will achieve the required outcome with an acceptable limit of risk and minimum cost. The idea of optimizing maintenance activities is promising to improve uptime, extend the total life cycle of physical asset and assure safe working conditions, while keeping within limit of maintenance budgets and environmental legislation.

Traditional approaches to large scale maintenance have proven successful in the aspects of safety, but there exist some limitations in terms of economy, life length and track possession time. This necessitates the development and application of model based decision support tools for the optimisation of maintenance. The optimisation procedure for high performance tamping, grinding and switches & crossing are discussed in the succeeding sections.

3.1 Application of optimization model for high performance grinding

Conventional grinding strategies are described in deliverable D4.5.1 of the project INNOTRACK (INNOTRACK 2008) are given in Table 6.
Grinding can be performed frequently that can be repeated up to 3 times per year (Nürnberg-Ingolstadt) to prevent cracks to grow after the initial stage or much more seldom as corrective grinding. Preventive grinding should be implemented on highly loaded track sections as they are new. When the rail to have larger cracks it might be difficult to take these away and at this later stage for cracks corrective grinding and milling are proper methods. Depending on the remaining life of the rail a corrective grinding strategy might be replaced by preventive grinding if all the remaining cracks can be removed.
Preventive grinding can be done on a cyclic on a time based or MGT based schedule. It can also be done condition based (prognostic grinding), but for this measurement technologies needs to be developed together with decision tools.

Table 6: Conventional grinding strategies with features and patterns

Cause for grinding	**Intervention Method**
Rolling contact fatigue (RCF) – top of rail – Imprints, Squats, Belgrospies - Initial stage - Late stage	 Preventive grinding Corrective grinding
Rolling contact fatigue (RCF) – gauge corner – Headchecks - Initial stage - Late stage	 Preventive grinding (gauge corner relief) Corrective grinding (gauge corner relief)
Transversal profile – Equivalent conicity	Preventive grinding
Longitudinal profile – Corrugation	Corrective grinding

3.2 Modelling Procedure

The model for calculation of track possession time, with resources and life cycle costing are given at *Figure 16*. This model considers 0.2 mm metal removal while grinding similar to INNOTRACK as discussed in subsequent sections. For the track replacement, grinding parameters are considered with their limits and timings.

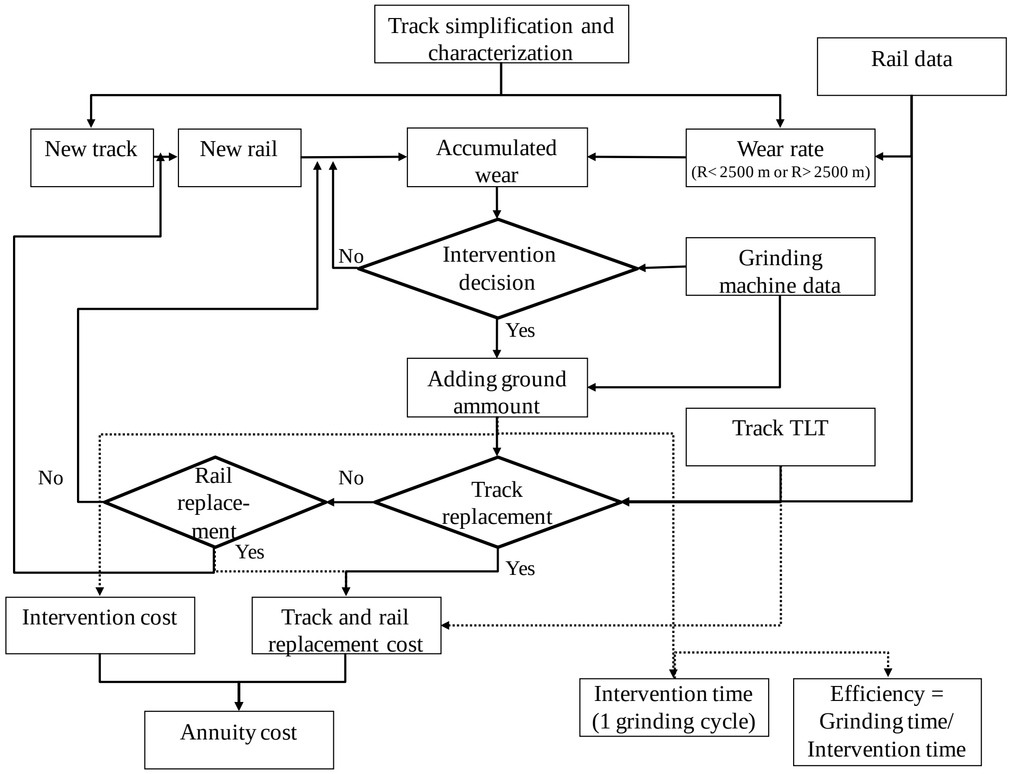


Figure 16: Theoretical framework of the mathematical model for calculating track possession time and life cycle cost for grinding

3.3 Track possession time

The data used in the model are taken from the Value Stream Mapping, and INNOTRACK project and track data are taken from different Swedish track sections to give a variety of curves traffic. One of the track sections is also used for the tamping study, namely between Långsele and Mellansel with 23 freight trains and 4 passenger trains per day and approximately 12 MGT/year, see Figure 17.

The grinding machines that are been discussed within the project are: a conventional grinding machine with 48 stones and a High Speed Grinding train with 96 stones. The 48 stone-machine is able to remove 0.2 mm within two passes. The inherent capacity is 5 000 m/h. However, in UK the practice is to use a single pass with 64 stone machine operating in traffic (approximately 7 500 m/h), this is used as improved conventional grinder. The High Speed Grinding train is able to remove 0.1 mm within three passes. The capacity is over 28 000 m/hour. In practise the total production is 60 % of a given shift time or less, for both conventional and High Speed Grinding.

The situation on mixed lines within Europe is that the track possession time is getting shorter and shorter so it is difficult to achieve maintenance windows of 6 hours. Increasing the track possession time from 6 hours to 8 hours will decrease the total time in track with about 7 % as each shift will be

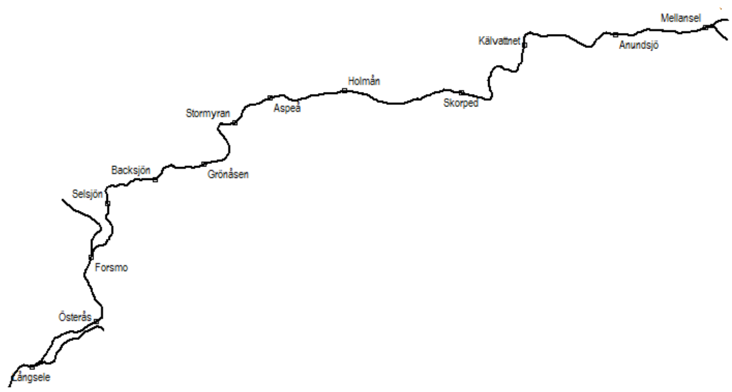


Figure 17 Track section 130 Långsele – Mellansel (Trafikverket, Sweden)

more efficient, but fewer shift will be needed. The conclusion is that to minimise the track possession time there are arguments to have long enough maintenance windows. When this is not possible higher machine speed, longer trains with more stones or high performance grinding trains are alternatives.

The track geometry selected for simulations has been chosen to represent all the infrastructure manager's tracks and match the criteria for lines and routes for this project. For instance, all sections have curve radius larger than 800 m, the line speed is less than 160 km/h and with a load of 20-60 MGT/year - for more information see the milestone 6 documents. Table 7 shows the different tracks/routes for these simulations.

Table 7: Track geometry for the simulations

Tracks/route	**130**	**814**	**912**
Amount of circular curves with R = 800 - 2500, in length [%]	40	2	18
Amount of transition curves with R = 800 - 2500, in length [%]	39	2	18
Amount of sections >2500 m, in length [%]	21	96	64
Track length [km]	90	49	48
Yearly traffic [MGT] Simulated traffic [MGT]	12 30	8 30	20 30
Rail/Material	60E/R260	60E/R260	60E/R260
Technical Life time, rail (TLT) [MGT]	600	600	600
Technical Life time, track (TLT) [MGT]	900	900	900

Table 8: Simulation parameters

Simulation parameter	***Conventional M48***	***64 stones grinder Improvement***	***HSG***	***Twin HSG Improvement***
Machine	For conventional grinding, a 48 stone machine is used	64 stone machine is proposed to reduce time in track and is in practise in Great Britain and has been introduced in Germany	High Speed Grinding train has been in practise since 2006 in Germany	Proposal of improvement to reduce time in track
Number of passages	2	1	3	1
Grinding speed [km/h]	10	7.5	80	80
Transport speed between sections[2]	Curves 20 km/h Straight 40 km/h To depot 80 km/h	Curves 20 km/h Straight 50 km/h To depot 80 km/h	No need for transport 80 km/h	No need for transport 80 km/h
Grinding depth [mm]	0.2	0.2	0.1	0.1
Need of refresh grinding stones	0	0	0.9	0.9
Time needed for slag picking during last pass/post-measurement [minutes/km]	3.75	0.625	0	0
Removing fixed installations [minutes]	15	0	0	0
Time to end possession	20	20	0	0
Margin for not starting grinding a new section [minutes]	15	15	0	0
Grinding interval curves [MGT]	20	20	15	15
Grinding interval tangent [MGT]	40	40	15	15

The simulation is made with random numbers on actual data of track sections. Each calculated point is based on average values of 10 simulations. The track section is divided into curves which are ground every time and tangent track that is ground every alternate period of the time by the conventional grinder and with the High Speed Grinding train every time. There is a depot on either side of the track section and sometimes in the middle of a track section. For each shift the grinding train must be able to reach the depot within the shift time and a transportation of 40 km takes more

[2] Transport is defined as the distance between different sections if not the whole distance is ground. Due to the need of grinding curves more often longer straight portion is not ground every time and transportation is needed within the possession time. If 2 or 4 pass grinding is used, transport is also needed to come to the next section that should be ground.

than 20 minutes. Because there is a start-up and close down time, short shift length (less than 4 hours) show a strong influence on the total possession time needed to grind a track section. Above 6 hours the influence is not so great. For the conventional grinder there is a waiting time during the shift. The reasons might be different for different infrastructure managers. In Germany pre and post measurements is done as part of the grinding possession time and in Sweden request for passing a main signal is estimated to take 15 minutes per signal. In the simulation 3.75 minutes is added per km for the last passage, which reduces the possible possession time with 20 %.

In alignment with the lean philosophy, an 8 step approach which includes Value Stream Mapping has been utilised to address the following waste:

- Transportation
- Communication
- Confirmation
- Waiting
- Set up and withdrawal
- Planning and preparation
- And other forms of waste relevant in the railway industries

The invention on a conventional grinder is based on the following ideas (VSM headings within parenthesis, refer to the bullet list above):

- Increased possession time per shift (shorter shift than 4 hours should be avoided) *(Transportation & Resources)*
- Reducing time for picking slag and post measurement *(Waiting)*
- Single pass (*Operation*)
- Increased grinding speed by using a longer grinding machine with 64 stones that is capable to grind 1 pass in 7.5 km/h instead of 2 pass in 10 km/h each (has been practised in Great Britain) *(Resources & Equipment)*
- Reduce the time spent traversing the unground sections by increasing transportation speed *(Transportation)*
- Enable grinders to grind also places with axle counters and rail lubricators without removing and remounting

The following ideas have not been introduced in the simulation:

- Shorter travelling distance from stabling point
- Increased grinding speed to 15 km/h
- Avoid separate pre and post-maintenance measurement runs
- Avoid planning for longer shift than is utilised (in the model 0.25 hours is estimated to be the margin)
- Timetabled slow moving train

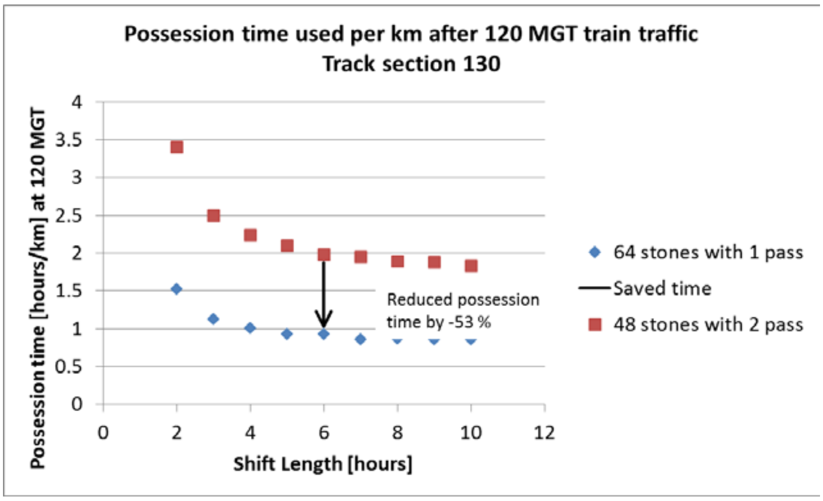


Figure 18 Need of total possession time as a function of available shift length for track section 130

Figure 18 shows an example of possible reduction in possession time by removing waiting time and reducing number of passes and thereby increase the inherent grinding speed. The possible reduction depends on how the track section is built. A high amount of long curves, which is ground more often than straight track, will utilise increased speed better than shorter curves. This is a reason to analyse three different track sections which is shown in Figure 19. The simulation shows improvements in the order of 50 % are possible. The lowest occupation time is on a track with low amount of curves; on the other hand there is less sparking time in this case as well.

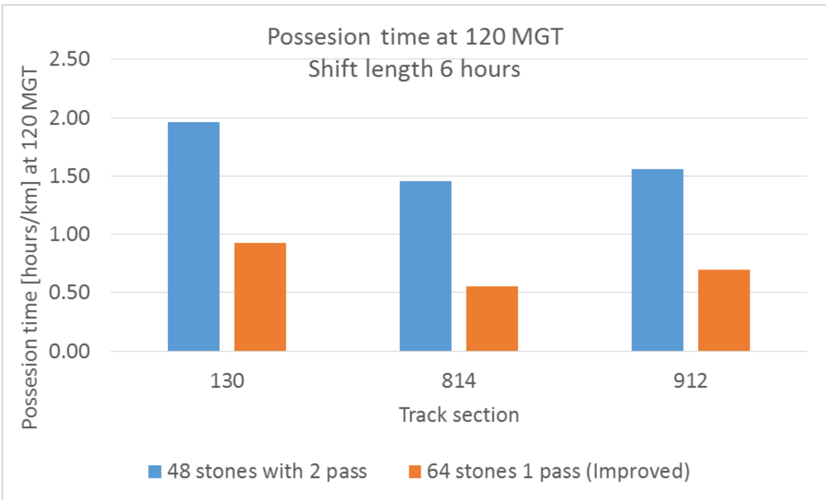


Figure 19 Need of total possession time as a function of track section at 6 hours shift length

3.4 Comparison with High Speed Grinding

High Speed Grinding is not using the possession time in the same way as the conventional grinding train. While the speed is 80 km/h it is seen as a normal train by the train dispatcher and given a train number instead of being a seen as close down of part of a track section. This gives several advantages in planning and execution of the grinding work. First of all the actual planning of the work can be done later as occupation time is less it is easier to fit a train into the plan than a work which requires closing the track. Secondly during the execution of the grinding there are no stops due to slag collections or waiting for signals. A third advantage is that all tracks are ground about 0.1 mm per campaign instead of 0.2 mm by the conventional grinder so the total life time will be longer in curves with a High Speed Grinding train. There might be a need to use a conventional grinder in combination with the High Speed Grinding train. The reason to use a conventional grinder is to restore the transversal profile. This is necessary when the curve radius is small and especially if an anti-head check profile is in use. This question has not been thoroughly discussed within AUTOMAIN, since the curve radius was stated to be above 800 meter. Therefore in the LCC-calculation, it has been assumed that re-profiling is not necessary, which is the experience from Deutsche Bahn on lines with high speed traffic.

Not only High Speed Grinding could be scheduled, also conventional grinding train can be scheduled, which is done in United Kingdom. This enables some of the above mentioned advantages.

The High Speed Grinding train needs to replace the grinding stones after 50 ground kilometers. A typical cycle time for 50km grinding can be broken down to 38 minutes of grinding (spark time) followed by 52 minutes of stone exchanging and locomotive shunting, in total 1 hour and 30 minutes. This means that it is possible to reach up to 100 km of ground track in a 9 hour shift with a material removal rate of 0.1mm since that requires three passes. The onboard dust and metal friction containers are emptied during non-operational hours.

To compare with the conventional grinder the following calculation is based on 6 hour- shift. The possession time during a 6 hour-shift is just 3 hours as the time for exchanging stones is done on a siding. This reduces the possession time compared to conventional grinding with about 67 %, see Figure 20.

On a track with less curves (track section 814) the conventional grinder with 64 stones do not spend more time than the HSG train (+27 %) as a consequence that the grinding interval for a conventional grinder is 40 MGT in straight track and for the High Speed Grinding train 15 MGT. An improvement of a High Speed Grinding train would be to have two connected grinders which should enable to grind 1 pass instead of 3 pass to remove 0.1 mm. This is shown in Figure 21 as “Twin HSG”.

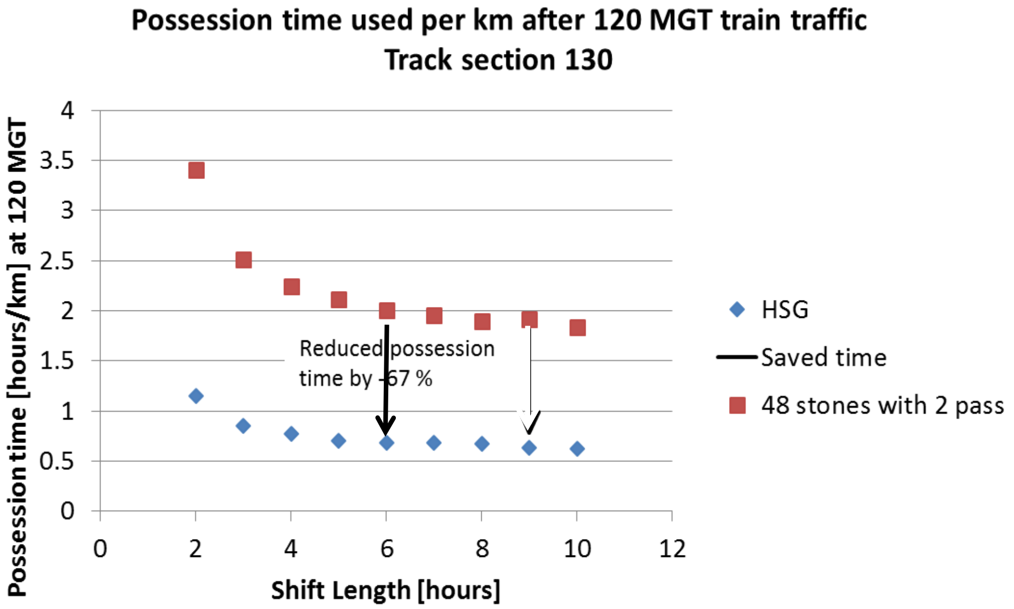


Figure 20: Track possession time used for conventional and High Speed Grinding train at 120 MGT

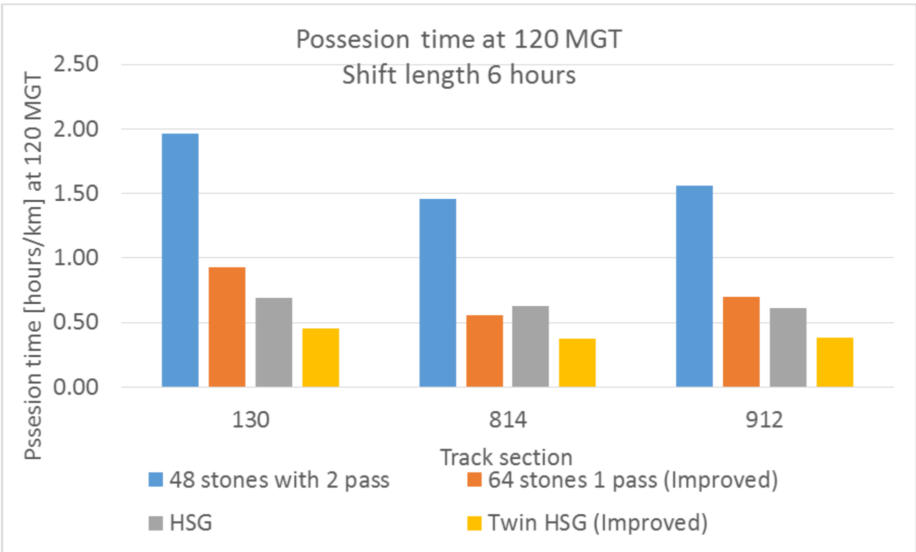


Figure 21: Need of total possession time as a function of track section at 9 hours shift length

3.5 Cost model

Predetermined grinding is based on the assumption that the growth of cracks is slower than the yearly wear and grinding depth. In AUTOMAIN 20 MGT in curves (800-2500 m) and 40 MGT in tangent track (R>2 500 m) is assumed for conventional grinder. For a High Speed Grinding train the total length is ground with an interval of 15 MGT (0.1 mm metal removal with 3 pass) or 30 MGT (0.2 mm metal removal with 6 pass) and therefore it is even more efficient on a line with a high portion of curves than on a line dominated by tangent tracks compared with conventional grinding.

The cost model is treating several possible parameters that can be different on different track sections. The most important parameters are:

- Track horizontal geometry (amount of curves)
- Track load (MGT/year)
- Rail data (wear rate and permissible wear depth, TLT for rail)
- Grinding machine data (number of passes, ground depth, speed, cost per shift, shift length)
- Maintenance window (permissible track possession time)

It has not been possible to incorporate all parameters in the LCC-calculations that have a great influence. Three important parameters that have been disregarded are:

- Cost for operational hindrances, such as re-routing trains and replacing passenger trains with buses, penalties and other fees, as well as administration cost for handling track possession time and train scheduling
- Opportunity cost for cancelled trains
- Re-profiling by conventional grinding when calculating cost for HSG
- Risk for rail break or acceleration of crack growth. There have been discussions that increasing grinding speed, pressure and total amount of ground material will at some level give lower quality in the ground surface. To avoid the risks to present unrealistic results the parameters used in the calculation is already in use or at least tested with acceptable result

Within this project there is no clear conclusion when the best choice is using conventional grinder or a High Speed Grinding train. On a general level it can be said that the both technologies competes depending on factors of how the machine can be utilised. The more costly a machine is the more important it is that the actual planning is very good and that the estimated amount of work can be done as it is planned. To be able to compare the different grinding methods the whole life cycle needs to be taken into consideration as well as local conditions. In such a calculation the track replacement will be the highest cost. The infrastructure managers has different philosophy on when to do the track replacement varying from 20 to 50 years (and in total load 500 to 900 MGT) so in these calculation a high value has been used, that is 40 years or 900 MGT. If both grinding methods will have the same life time of the track, the cost for track replacement will be the same and can be omitted. On lines with considerable amount of curves and more traffic the conventional grinder will grind away more material and therefore the TLT of the rail will be shorter and the annuity cost for rail replacement will go up. As mentioned earlier this will not be the case if High Speed Grinding will be combined with regular re-profiling as in the Netherlands.

Case study:

This case study has used data from track sections 130, 814 and 912.Figure *22* shows that the High Speed Grinding train can save money assuming all methods starts with a newly laid track (or replaced rail). In both improvement suggestions the cost will be lower. The figure shows the cost for track replacement, rail replacement due to wear or that the TLT is reached (after 20 years) and the grinding cost. The grinding cost is in the order of 5 -10 % of the total LCC and therefore the time of track replacement might be of interest to discuss further. It is in this case 30 years (900 MGT), by a good grinding strategy, under sleeper pads and good track alignment hopefully the TLT could be longer, which would lower the annual LCC.

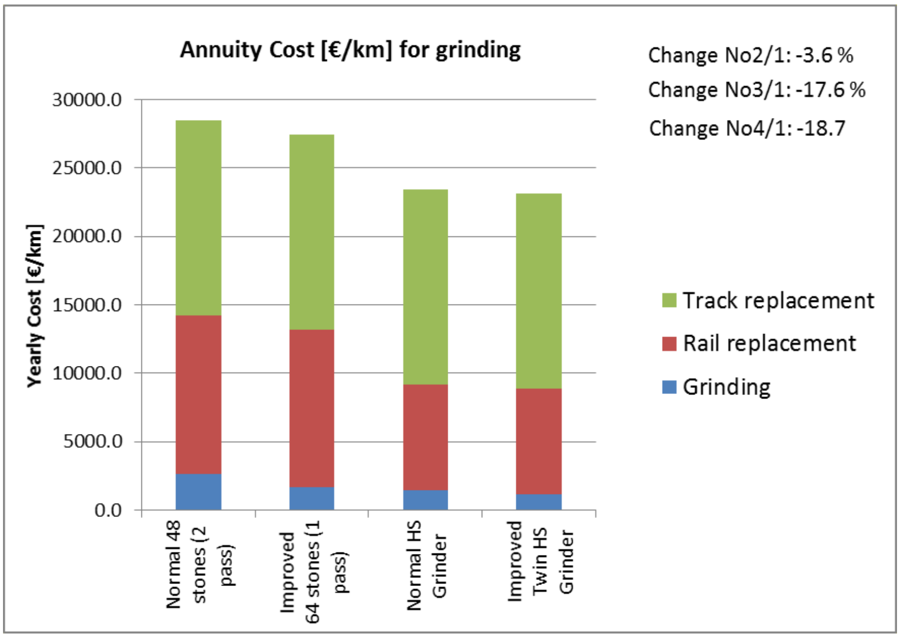


Figure 22 Annuity cost per km for track section 130 with 71 % curves (R< 2 500 m) with 30MGT per year

To be within the load interval discussed in AUTOMAIN the cost calculation is based on 30 MGT annual load. In Figure 23, it is shown how the cost for conventional and for normal High Speed Grinding train varies depending on the annual load. The cost is normalised to be per 100 MGT. The lowest cost at 22.5 MGT depends on the fact that the TLT of track is 40 years in all cases and this corresponds to 900 MGT best.

Not only the parameter annual load will affect the calculations and there are several parameters that might change the total cost such as assumed technical life length (TLT) of rail respectively track, shift length, wear rate, minimal removal and so on. Therefore only general conclusions should be drawn from these calculations as the input parameter are general for the project and not specific for a certain situation.

General conclusions are that long possession time per shift and high grinding efficiency are the two most important parameters to lower life cycle cost. An improved conventional grinding machine will have about the same order of cost as the High Speed Grinding train, but will most probably give earlier replacement of rail in curves than the High Speed Grinding train so the LCC-cost is slightly higher.

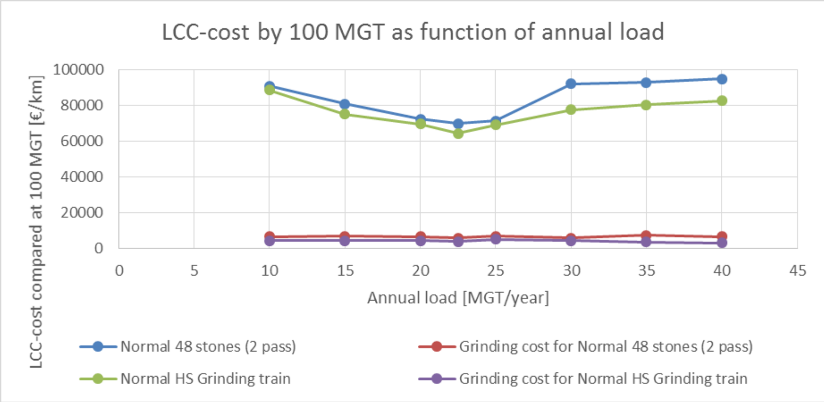


Figure 23 LCC-cost at 100 MGT as function of annual load

In Figure 24 the total cost is compared for 3 different track sections assuming 30 MGT as annual load. In all cases the supposed improvements or the use of High Speed Grinding train will give a lower cost than the conventional grinder.

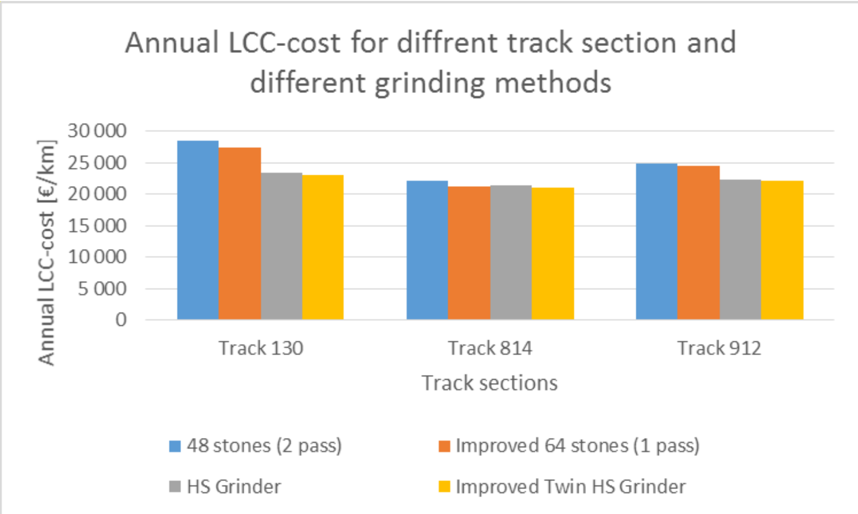


Figure 24 Comparison in cost savings for several track sections

4. Application of optimization model for high performance tamping

4.1 Track geometry monitoring and essential features

High performance tamping demands the application of model based principle for the optimisation of the process. The essential features of model based optimisation procedure for high performance tamping include:

i. Behaviour of track structure in deterioration

   The possibility of continuous or consecutive monitoring runs at time intervals is an important consideration for successful condition based maintenance management. This gives engineering insight into temporal failure phenomena including the behaviour of infrastructure component over time. The deterioration of track structure is modelled using empirical, statistical or artificial intelligence approach depending on the data available and modelling condition. This allows prognostic approach of condition based maintenance which facilitates condition forecasting, maintenance planning and optimization of intervention time.

ii. Pattern of track geometry error

   A combination of experience, measurement data and historical maintenance data can be used to recognize the pattern of geometry error. The occurrence of geometry defect can be analysed in terms of frequency of its observation and also the wavelength description of the defect. These are important information for maintenance planning and selection of appropriate strategy for optimum quality at minimum time and cost. Statistical or empirical model of the frequency of occurrence of geometry defect is essential for maintenance need analysis and optimum track allocation and utilisation. Table 9 gives some information about pattern of track geometry error as may be needed in the development of an optimum tamping strategy.

iii. Appropriate intervention threshold

   It refers to the value of the track geometry parameter that must be reached before measures are considered or taken within a period of time or immediately. The selection of the appropriate intervention limit is an essential factor that affects the amount of track geometry quality that is recovered after intervention. The values of these limits are usually given as a function of speed. It is essential to mention that late intervention close to the immediate action limit could give initial time savings but result into loss of quality necessitating shorter intervention interval at the later age of the track. Further information on intervention threshold can be read from European standard on Railway applications - Track - Track geometry quality - Part 5: Geometric quality levels, EN 13848-5, (CEN 2010).

iv. Recovery of track after intervention

   The extent of improvement achieved after tamping is basically influenced by the local conditions such as track quality at tamping, age of track component, tamping technique, number of previous tamping, ballast condition and human factor. Ability to capture the recovery characteristic of the track and also project the change in this characteristic over a number of tamping is a required element in a long term prognostics of track behaviours and maintenance need. In addition to this, stone blowing is considered as an established practice to improve the recovery of track especially towards the end of life of the track and extend its remaining useful life (For details on stone blowing see reference[3].)

It is important to mention that IM needs to practice absolute tamping of the track (restoration to the designed position) to maintain a correct stress free temperature.

Table 9: Pattern of track geometry error

Features	**Pattern**	**Intervention method**
Frequency of occurrence	Frequent or repeated occurrence	Line tamping/ prognostics or preventive tamping
	Occasional and scattered	Segment(area) tamping
	Spot failure	Spot taming / Corrective tamping strategy
Dominant Wavelength of occurrence	20-100	Absolute/Elimination correction tamping
	3-20 m	Relative or smoothening tamping
	1-3m	Rail smoothening

4.2 Case study

One of the line sections of the Swedish transport administration network (Trafikverket) is used as a case study for analysis and optimization of track possession time for tamping. The line section is one of the sections used in for grinding optimization. It is a 90 km single track which is basically a freight line with an average of 34 freight trains and 2 passenger trains. The axle load is 25ton with maximum load per meter of 8ton/m and also average annual tonnage of 12MGT. In this case study, machine parks are located at the extreme stations of the line section and it is assumed that the tampers are picked up and returned to these stations at every shift.

4.3 Track possession time

The strategy used in the simulation is a combination of preventive and corrective strategy. The preventive strategy is done at predetermined interval while corrective is done to repair spot failures which occur in between the tamping cycles.

The input data into the simulation considers the result from lean analysis of tamping done in WP2 see Table 10. The values used are adapted to make the simulation relevant to the line section under consideration.

Table 10: Data used for track possession simulation

Base Case	
Travelling speed	80km/h
Tamping speed	1.2km/h
Switch tamping	30-70mins*
Confirmation time	30mins

[3] Supplemental Report on the Use, Benefits and Limitations of Stoneblowing

Communication time	20mins
Waiting time	20mins
Preparation time	10mins
Time range for single failure correction	45-120mins**

* The tamping time of a switch depends on the type or model of the switch, for example it takes between 30 and 40minutes to tamp a switch type 1:9 (lift = 0-30mm) while it takes between 55 and 65minutes to tamp a switch type 1:20 with same lift.

** The time to correct a single failure varies depending on what is to be done and the length of the isolated defect to be corrected. It is worthy to mention that a special single failure correction machine has higher efficiency, it might require less time.

The first investigation is to see the effect of maintenance window or length of shift on track possession time needed for tamping the whole track length. The result shown in Figure 25 indicates an exponential decay function; short maintenance window requires several shifts and excessive long track possession time to complete a tamping cycle on the track section. Increasing the maintenance windows leads to an exponential reduction of the time required to tamp the whole section. Since the breakdown of activities during maintenance shift can be classified into three categories: value added task, necessary non value added task and non-value added task, adequate length of the maintenance shift is needed for augmented utilisation of the track possession time. Optimum possession length is required to reduce the impact of necessary non-value added tasks. However elimination of the non-value added task should be aimed at in order to improve the status quo. Figure 25 suggests a maintenance window above five hours for optimal reduction of track possession time.

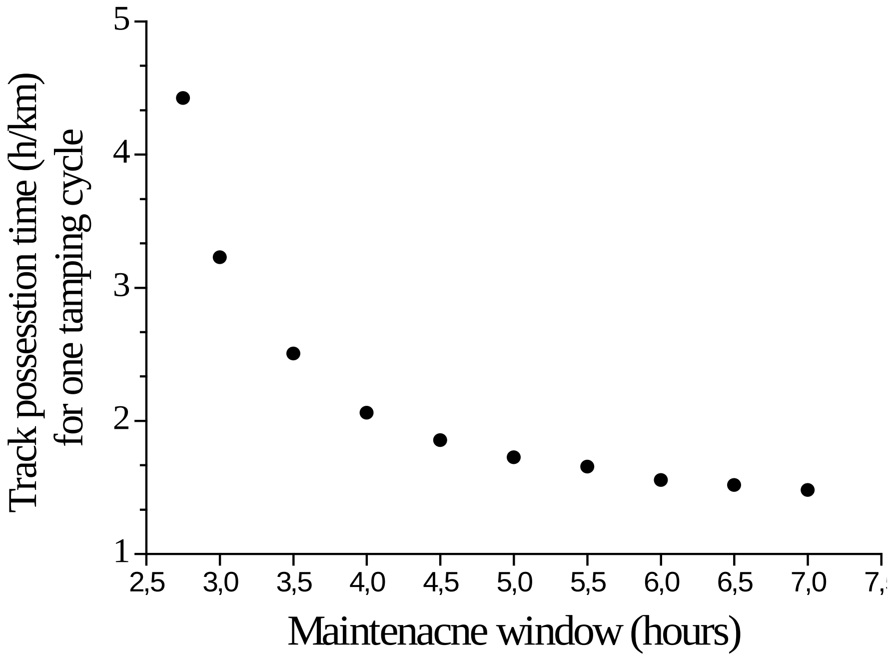


Figure 25: Maintenance window and track possession time for a complete tamping cycle

Furthermore, a maintenance window of 6hrs is used for further investigation of the best practices and improvement suggested in D4.2. To investigate the potential benefit of each improvement possibility, two cases were simulated for 10% and 40% improvement in the activities in a tamping process. Figure 26 shows that 10% reduction in the time needed for non-value added tasks will give close to 1.56% reduction in the total track possession time while 10% increase in the necessary non-value added task will give 0.9%. Similarly 10% increase in the tamping speed will give about 6% reduction in the possession time while an overall reduction of 11% can be achieved if all the tasks are improved by 10%.

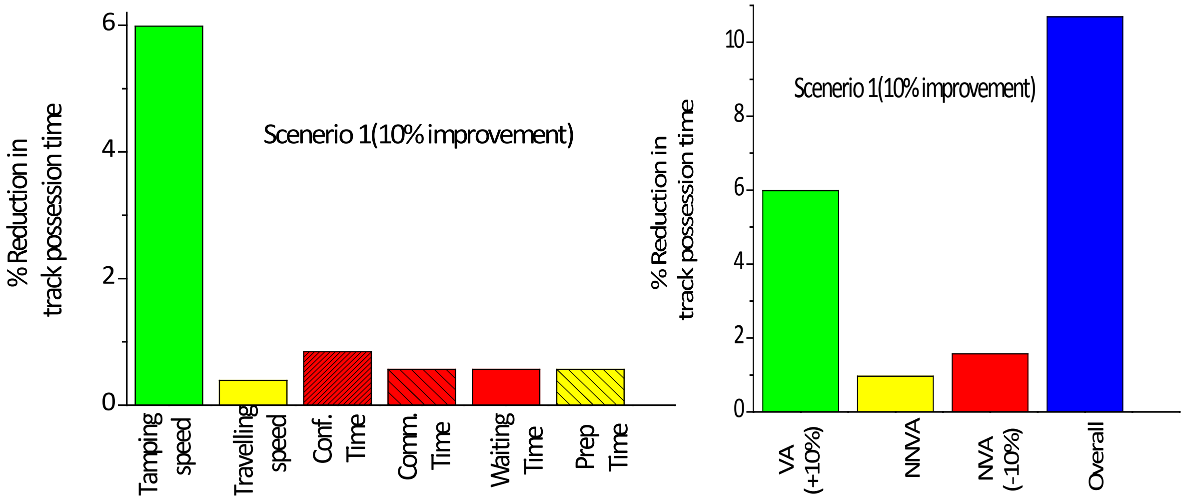
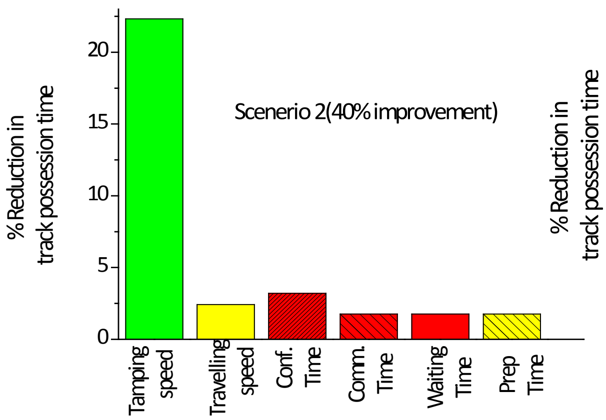


Figure 26: Reduction in track possession time for a tamping cycle with 10% improvement.

VA: Value-added task (e.g. actual tamping time), NNVA: Necessary non-value added task (Travelling, preparation time), NVA: Non-value added task (waiting, communication, confirmation)

Furthermore, Figure 27 shows that 40% improvement in the time for value added task, necessary non-value added tasks and non-value added tasks will give about 22%, 6% and 10% reduction in the possession time respectively. In addition to this an overall reduction of 35% can be achieved if all the tasks are improved by 40%. Overall, Figure 26 and Figure 27 show that maximum benefit is possible if tamping speed is improved.



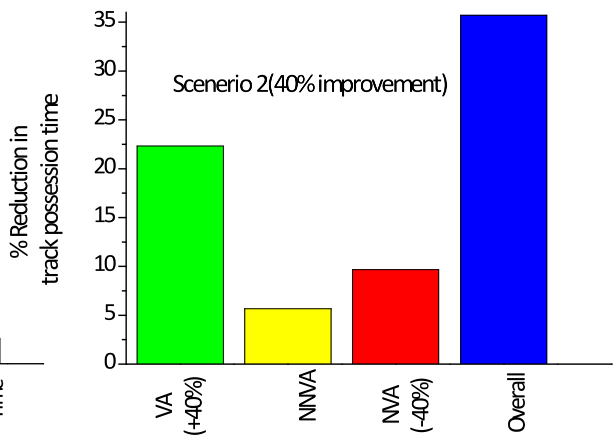


Figure 27: Reduction in track possession time for a tamping cycle with 40% improvement
VA: Value-added task (e.g. actual tamping time), NNVA: Necessary non-value added task (Travelling, preparation time), NVA: Non-value added task (waiting, communication, confirmation)

Furthermore, an optimum strategy is required to have additional reduction in the track possession time. An optimum strategy will give appropriate combination of predetermined line tamping and corrective measures for isolated local geometry defect in weak zones and critical spots. The number of corrective intervention or spot failure is modelled using stochastic approach. A historical data collected from the line section is used to develop a counting process for the isolated local geometry failure which is described using a non-homogenous Poisson process. The parameters of the model are estimated and then used to predict the number of failures that will be expected in the future.

Figure 28 shows the growth of the number of local geometry defect as a function of time that has elapsed after major intervention.

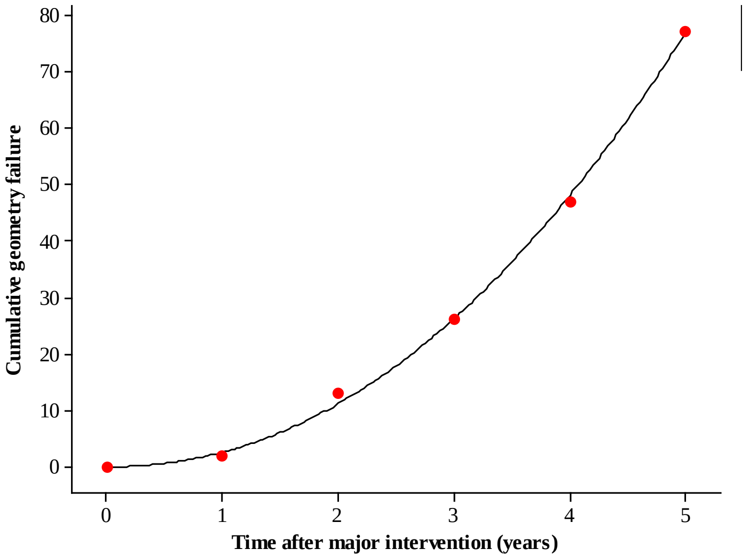


Figure 28: Cumulative intensity function for isolated local failure

The estimated number of isolated failure over the entire line section represents the number of occasions where spot failure correction will be needed. The number of isolated defect was estimated for different length of tamping cycle (2-13years) over a finite planning horizon and then the required track possession time per year was estimated and then plotted. A planning horizon of 13years with total tonnage of approximately 150MGT was selected. This was based on the assumption that after this horizon, other intervention measures such as ballast cleaning, rail change etc. will be necessary. The tamping interval that gives the minimum track possession time is considered to be the optimum for a high performance tamping. As given in Table 10, the time required to correct spot failures varies between 0.75hours and 2hours. The historical data collected for spot failure correction in the case study was fitted using a lognormal distribution, mean of 1.12hour with and 80% confidence limits between 0.93hour and 1.43hour were obtained. These were then used in the track possession time simulation for three different scenarios: average, worse and best cases of spot failure intervention. Figure 29 shows the track possession for the average, worse and best cases of spot failure correction. From Figure 29, it could be seen that larger tamping interval has large range of total possession time due to the increased need to restore spot failures, which has a varying track possession time requirements. The optimum strategy from track possession point of view is to have a tamping interval of 6years, since it gives the minimum average track possession time of about 0.373hour per track kilometre with 80% confidence limit falling between 0.33 and 0.437hour.

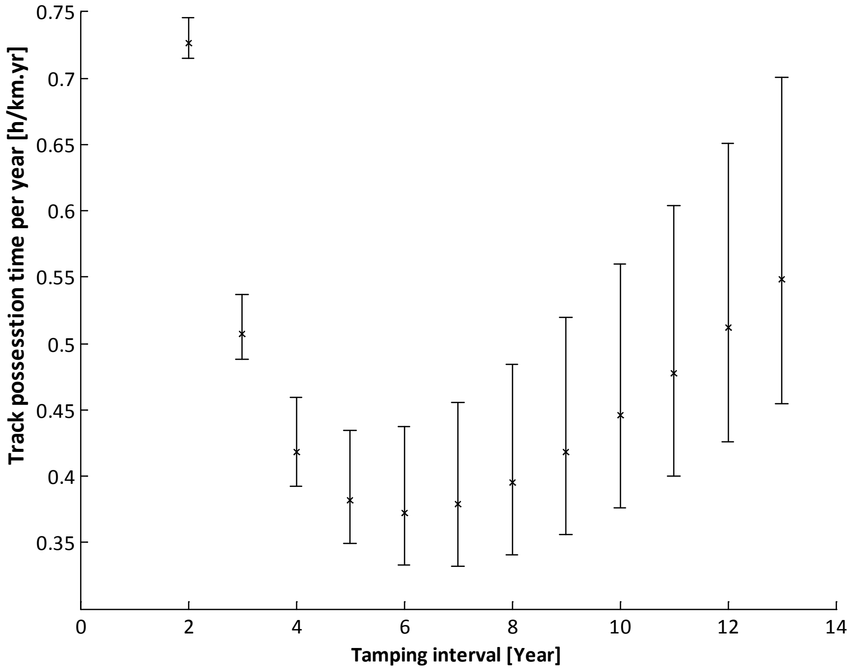


Figure 29: Optimum tamping interval for a planning horizon of 13 years (approx. 150MGT) with the average, worse and best scenarios of spot failure correction

4.4 Cost model

A LCC-model has been developed by DB and it is described in D4.1 section 3.1.2. However the results from the calculations are classified as confidential and can therefore not be presented in this deliverable. A further development in the capacity model for tamping will be to implement the model used by DB in the Capacity model.

5. Maintenance possession time simulation tool for switches & crossings

A tool for simulation of maintenance possession times has been constructed using Matlab. It can be used for simulation of modular S&C improvements that affects the active maintenance time or the time for preparation. Accordingly, the effect on KPI_4 of Deliverable 1.2 can be measured. The tool measures the possession time in track and also take into account the time that the maintenance team must wait for trains.

The model details are given in the next section, followed by sections containing demonstration, AUTOMAIN application and savings achieved.

5.1. Theoretical framework

Maintenance time in terms of travel, preparation, active maintenance and clearance can be estimated through experience and use of previous work order data. However the actual time to complete a particular maintenance task depends on the train time table, which is important for efficient planned work and for formulation of maintenance contracts, especially if the train time table changes over the contracting period. The model has a number of input and output parameters. The input parameters are as follows:

- Train time table
- Transportation time ($t_{Transp.}$)
- Non-value adding (NVA) time (t_{NVA}). Consist of preparation, confirmation, communication, waiting and lost time
- Active maintenance time (t_{Active})
- Minimum time for doing maintenance (t_{Min})
- Arrival point in the time table

Minimum time for doing maintenance ($t_{Min.}$) can be based on the active time. As an example, if the needed time for a maintenance activity is 150 min and t_{Min} is set to 10 % of that time, i.e. 15 min, then no maintenance will be carried out if the time left for maintenance between two trains is less than 15 min.

The output parameter is:

- Maintenance time: The time from that the maintenance team arrive till the work is finished and the track is cleared.

5.2. Demonstration of simulation

Given that t_{NVA} equals 10 min, t_{Active} equals 50 min and $t_{Min} = 0{,}1t_{Active} = 5$ min, the maintenance time becomes 109 minutes in the example below, i.e. 118 % more than the 50 active minutes required; see *Figure 30*. The train time table is for the Rautas station of the Swedish Iron Ore Line.

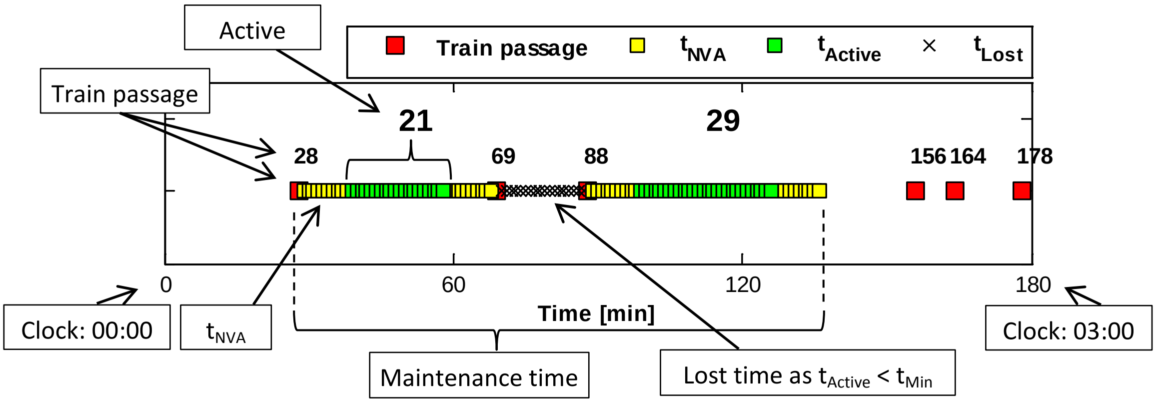
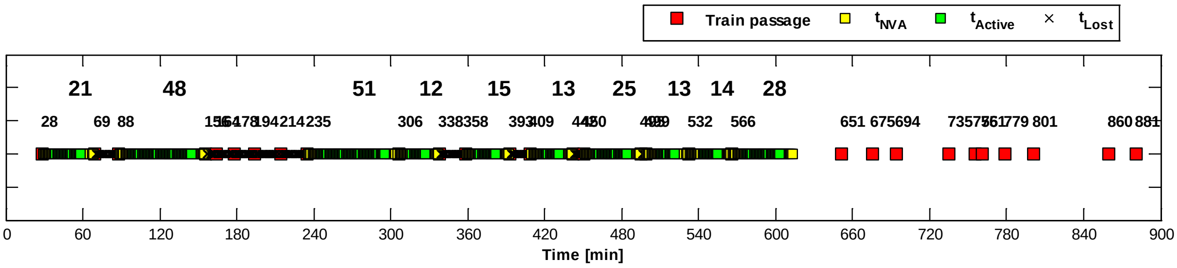


Figure 30: Description of simulation results.

Interviews with a maintenance contractor in Sweden have been carried out to know the active time needed for various maintenance activities on S&Cs (*Table 11*). For example, point replacement due to wear and rolling takes about 4 hours (240 min) in track. If we reduce t_{NVA} and t_{Active} with 40 %, then the maintenance time will be reduced with 55 % (1 - 144/240); see *Figure 31*.

a)
t_{NVA} = 10 min
t_{Active} = 240 min
$t_{Min.}$ = 0.05t_{Active} = 12 min
Maintenance time = 586 min



b)
t_{NVA} = 10*0,6 = 6 min
t_{Active} = 240*0,6 = 144 min
$t_{Min.}$ = 0.05t_{Active} = 7,2 min
Maintenance time = 261 min

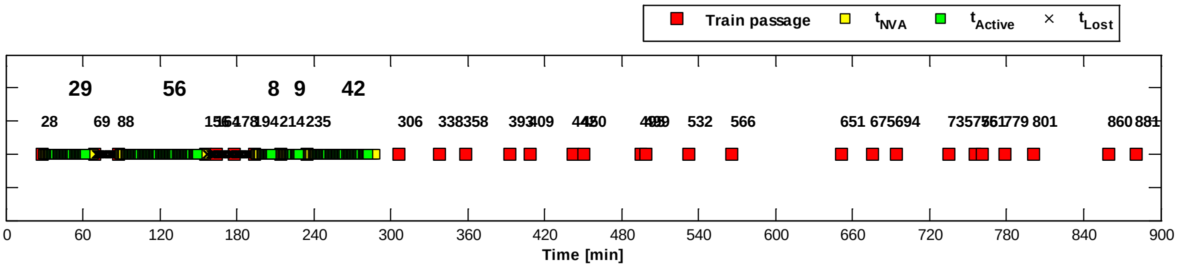


Figure 31: Effect of 40 % reduction on t_{NVA} and t_{Active} on the maintenance time. Gives 55 % reduction on the maintenance time from (a) to (b), calculated as 1-261/586 = 0,45.

Interview results are given in *Table 11*. The active time from contractor experience is given as 'min' and 'max'. Maintenance activities that take longer time (bold text) are more affected by train operations. As an example, the point replacement takes between 240 and 480 min depending on traffic.

Table 11: Interview with maintenance contractor regarding maintenance time of S&Cs.

Subsystem/ component	**Failure cause**	**Action**	**From contractor**		**Comment**
			Active time needed [min]		
			Min	**Max**	
Motor sys.	Adjustment or wear	Readjust or replace	15	30	Only friction coupling Force = f(temp).
Screw	Screw locking broken	Replace	5	-	Screw nut locking mechanism broken
Point ctrl sys.	Not in pos.		15	30	Seldom failed connector. Sometimes ice
Motor sys.	Power overload	Adjustment of clutch	15	30	
Measurement codes/margins	Metal rolling	Grinding or replacement of rail component	60	240 (with traffic)	Depends on the traffic. Iron ore line has very high loads
	Sleeper	Replacement	240	480 (with traffic)	5 sleepers = 8 h. 4h in track. Wrong track gauge. Concrete sleeper; can drill new hole for screw
Crossing point (frog)	Wear and rolling	Replacement	240	480 (with traffic)	4h in track, takes one night. Disassemble and assemble takes long time
		Welding	60	-	
Check rail	Rolling	Replacement	60	-	
		Welding	60	-	
Ballast	Too much/little		5	-	Depends on the amount
Geometry	Faulty pos.	S&C tamper	60	-	2-3 in Sweden
		Wheel loader with tamper tool	120	-	Emergency, for less than 20 m

5.3. Case study

Two studies have been carried out, one on crossing (frog) replacement and another on optimal maintenance window in-between regular departures, i.e. passenger traffic in urban areas.

5.3.1. Dual welding teams for crossing replacement

Value stream mapping (VSM) has been carried out for a crossing (frog) replacement in Gnesta municipality, Sweden. The number of moments for a replacement was found to be (see *Figure 32* for explanation):

Preparation	5	moments
Preparatory track safety (S1)	2	moments
Transportation and set-up (TS1)	1	moment
Production/maintenance	66	moments
Terminating track safety (S2)	1	moment
Clearance and transportation TS2	2	moments
Concluding/after work	2	moments

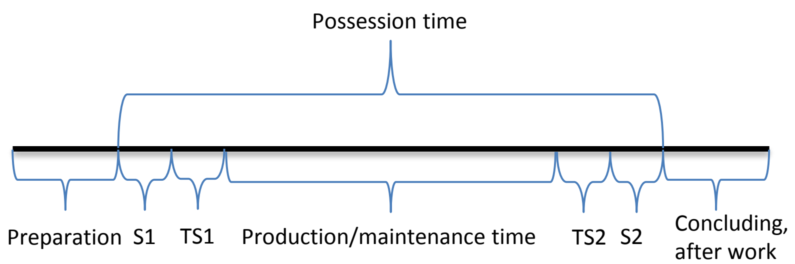


Figure 32: Details of possession, preparation and concluding time after work.
Refer to Deliverable D4.2.

A frog replacement takes 4-5 hours with current practice, using one welding team. From the VSM, it was found that the production/maintenance moments can be reduced from 66 moments to 40 moments, i.e. 40 %. It is estimated that the time saving for those moments will then be about 40 %. The additional persons can also assist in the other moments to reduce the possession time even more. Thus, the work could be finished in 3-4 hours.

A frog requires four welds, where two welds must be completed before any trains can pass, if not using additional fixtures. Two welds can be finished after 2-2½ hours with current practice, and after 1-1½ hours with use of two welding teams. Therefore, a train time table window of 2-3 hours is required. See *Table 12* for a summary.

Table 12: Current and new practice times for crossing replacement.

	Welding teams	Possession time [h]	Welding [h]	Time when train can pass [h]
Current practice	1 (6 persons)	4	2	2½
Dual weld teams	2 (8 persons)	3	1,5	1½

The results from three hours window can be seen in *Figure 33*. The time table used is a modified version of Rautas station of the Swedish Iron Ore Line to include a time window of three hours. The time saving is 51 % (1-180/367). However, with current practice it is common to use two night shifts, i.e. 2x3 hours. The results answer to KPI_4 given in deliverable D1.2.

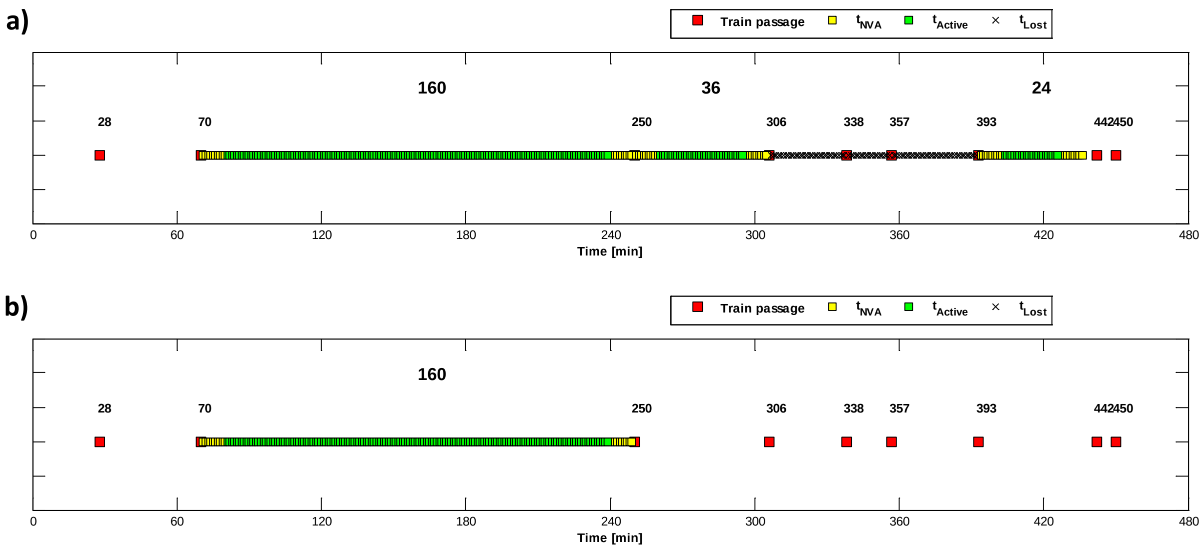


Figure 33: Result from three hours window. a) Current practice takes 367 min b) Dual weld teams takes 180 min. t_{NVA} and t_{Min} are both set to 10 min. The time saving is 51 %. Refer to Figure 30 for result interpretation.

5.3.2. Maintenance in-between regular departures

Optimal maintenance window in-between regular departures came up as a question within WP4. In contrast to freight trains, like the Swedish Iron Ore Line, passenger trains in urban areas have regular time tables. A fictional maintenance work of 120 minutes has been simulated with regular time tables of different frequencies. See *Figure 34*. It can be seen that the maintenance time starts to approach an asymptote at 40 minutes train frequency. The optimal window size regarding train service and maintenance cost can therefore be considered as 40 minutes in this particular example.

It gives 35 % saving compared to a train frequency of 20 minutes. t_{NVA} was set to 5 min and t_{Min} to 10 min, however, t_{NVA} depends on the speed of the track.

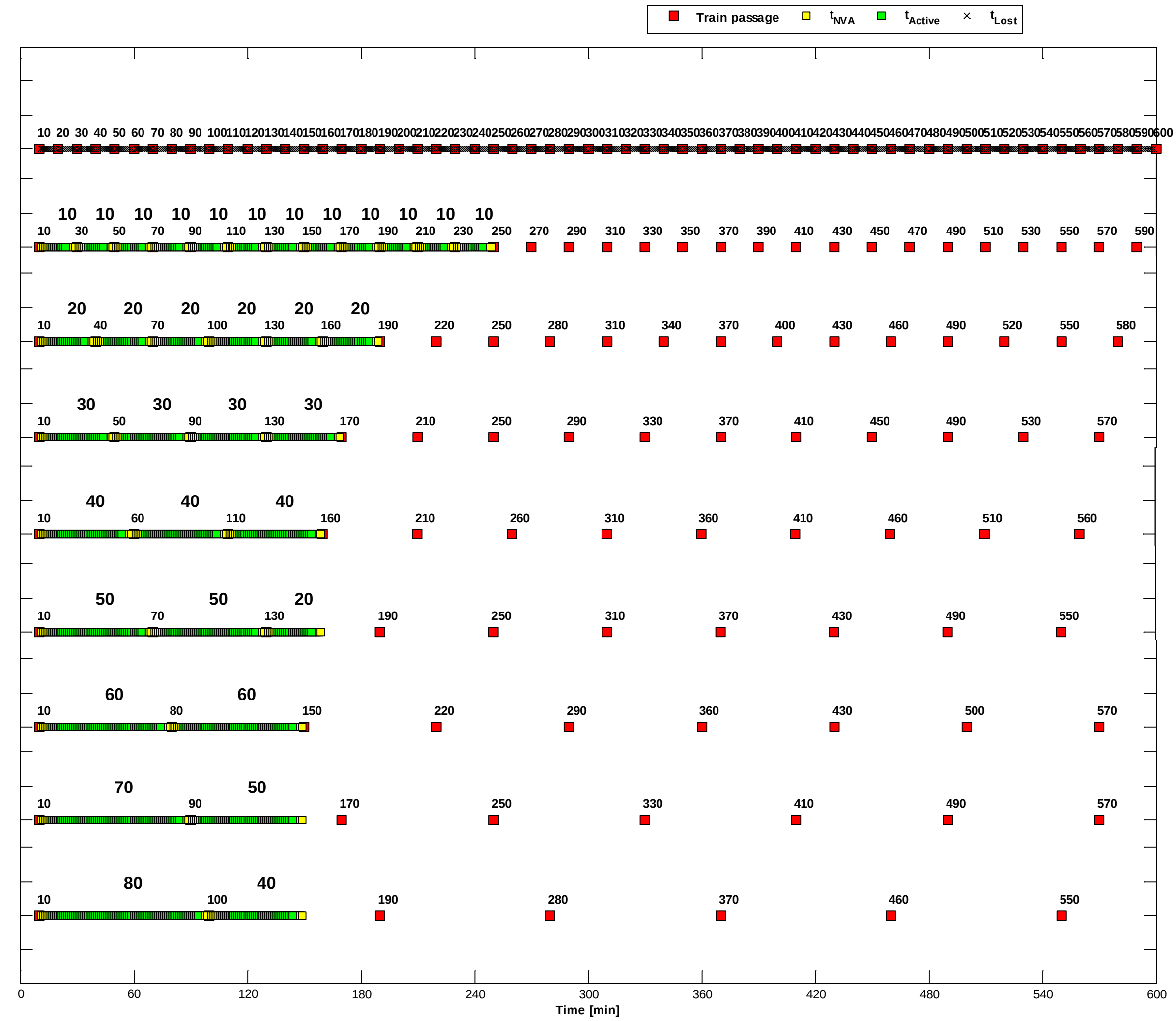


Figure 34: Maintenance work of 120 minutes in-between trains with various regular departures frequencies. t_{NVA} equals 5 min and t_{Min} equals 10 min. The maintenance time starts stabilising at 40 minutes train interval, thus it could be considered as optimal.

6. Summary of results and Conclusions

6.1. Key Findings

This report has presented three models and three case studies for the optimization of track possession time for grinding, tamping and switches & crossing maintenance. In addition to these, cost model is also presented for grinding. The key findings of the analysis and optimization are given below:

6.1.1. Optimization of track possession time for grinding

The approach proposed for the optimisation of track possession time for grinding has considered the following alternatives; conventional grinding with 48 stones, conventional grinding with 64 stones (with improved process efficiency), High Speed grinding and twin High Speed Grinding. The concluding remarks of the case study are:

- Long enough maintenance windows is necessary to minimise track possession time needed for grinding.
- The use of improved conventional grinding with 64 stones shows that reduction in track possession time in the order of 50 % is possible. This reduction depends on the layout of the track.
- HSG and twin HSG present good opportunity for the reduction of track possession time, in comparison with conventional grinding over 67% reduction in track possession time is possible.
- The grinding cost is in the order of 5 -10 % of the total LCC and the most significant cost element is the cost of track replacement. This makes decision on time to replace track crucial from LCC perspective.
- An improved conventional grinding machine will have about the same order of cost as the High Speed Grinder, but will most probably give earlier replacement of rail than the High Speed Grinder so the LCC-cost is slightly higher.
- General conclusions are that long possession time per shift and high grinding efficiency are the two most important parameters to lower life cycle cost.

6.1.2. Optimization of track possession time for tamping

A maintenance optimization approach consisting of predetermined and corrective policies has been described in this report. This presents the opportunity of improving the maintenance quality (condition and life span of track) and track possession time. Following the result of the case study presented with this approach, the following conclusion could be deduced:

- Adequate maintenance window leads to reduced track possession time that will be required on the long run. For the case study about 5 hours appears optimal, since further increase in maintenance window give very small additional benefits.

- Optimum possession length is required to reduce the impact of necessary non-value added tasks.

- Total elimination of unnecessary non-value added task will provide additional track possession time though small.
- Improvement of tamping speed gives the highest reduction in track possession time.
- 10% improvement in the tamping activities (travelling speed, tamping speed and other non-value added tasks) gives 11% reduction in the track possession time required for tamping the 90km line while 40% improvement gives about 35% reduction.
- The behaviour of the track becomes unreliable if the tamping cycle becomes too large or in the absence of one, owing to increased number of spot failure with high variation in track possession time.
- The number of isolated geometry failure over time follows a power law process. Following this, an optimum strategy from track possession point of view is to have a tamping interval of 6years. This prevents excessive periodic line tamping and too many spot tamping which reduce the life of the track and increases LCC as well.

6.1.3. Maintenance possession time simulation tool for switches & crossings

An algorithm for simulating maintenance in-between trains was developed. Two studies was carried out, one on crossing (frog) replacement and another on optimal maintenance window in-between regular departures, i.e. urban areas.

Value stream mapping together with the simulation shows that a time saving of 50 % in crossing replacement is possible which is answering to KPI_4 in previous Section 2.4.1. However, it requires two welding teams compared to one in current practice, i.e. a maintenance team of eight people instead of six people. Refer back to *Figure 33*.

In the study on optimal maintenance window in-between regular departures, a fictional maintenance work of 120 minutes was simulated with regular time tables at different frequencies. Results indicates that 40 minutes train frequency could be considered as an optimal window size regarding train service and maintenance cost. It gives 35 % saving compared to a train frequency of 20 minutes. Refer back to *Figure 34*.

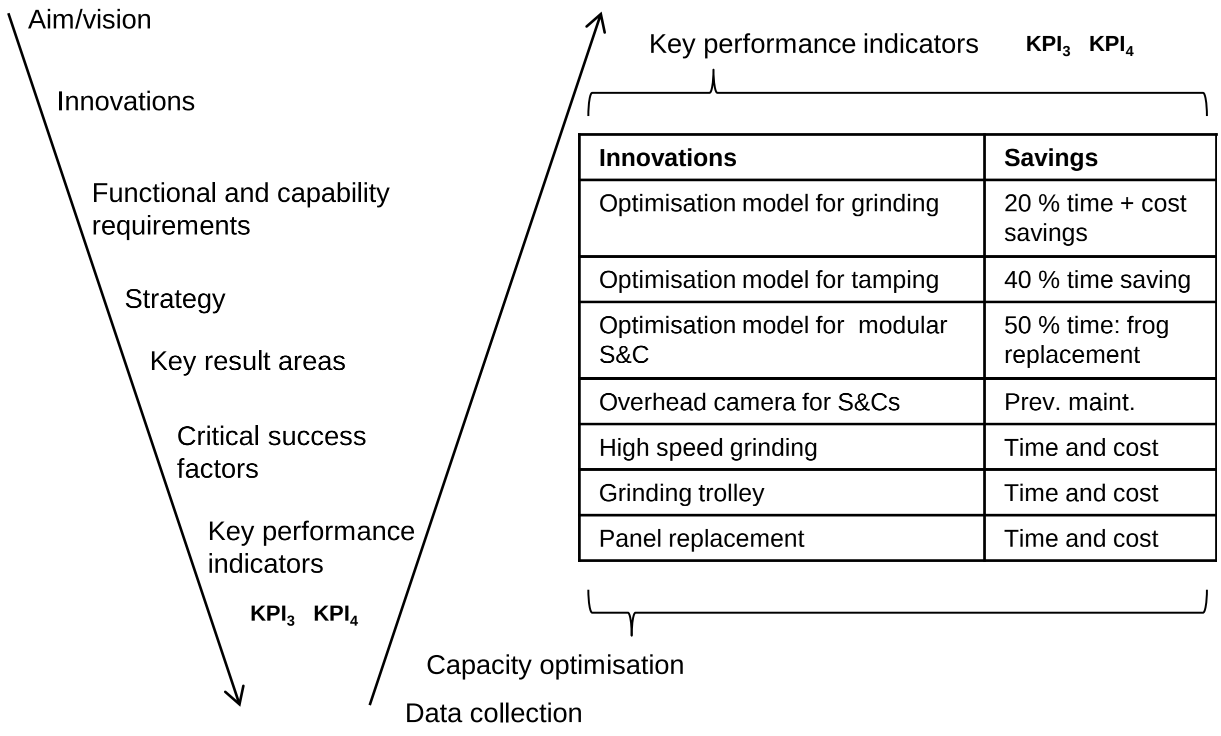
6.1.4. Link and effect model

The link and effect model was developed after a thorough literature review; see *Section 2.4* and related references. To achieve an efficient and effective performance measurement system, it was found that:

- A continuous improvement policy is essential, and in it needs to be easy to understand and follow. It will make the performance measurement system flexible too handle changes within organization, physical assets, goals and technology, besides be able to integrate other project initiatives. Assuring an easily understood continuous improvement process is necessary for communicating vision, mission, objectives and KPIs throughout the whole organization, from senior management to the operational level. Refer back to *Figure 6*.

- Key components of strategic planning needs to be clear within each organization. If the terminology and language is unclear or hard to reach; the performance measurement system is unclear and organizational units may not work aligned. Refer back to *Table 4*.
- Organize, document and regulate databases and performance indicators. Organizing and documenting parameters and indicators can save resources so that organizational units do not calculate the same indicators. Besides, the data quality and need will be known, and analysis can be automated making ordering of analysis unnecessary. Refer back to *Figure 7*.
- Indicators must be persistent, transparent and presented with background information for efficient management. An example is train delay; it should always be presented with its contributors. Related to the stock market where price development is seen with all major occurrences that may impact. Refer back to *Figure 8*.

The result from applying the link and effect model to AUTOMAIN WP4 is seen in *Figure 35*. The overall goal of AUTOMAIN is broken down to various KPIs for capacity optimization. The data collected has been analyzed and aggregated through simulation and models, and savings are calculated. The savings as linked with innovations (D4.1 and D2.1) and shown in the table below. The savings figure shows that AUTOMAN objective of reducing the maintenance possession time by 40% is achievable.



Innovations	Savings
Optimisation model for grinding	20 % time + cost savings
Optimisation model for tamping	40 % time saving
Optimisation model for modular S&C	50 % time: frog replacement
Overhead camera for S&Cs	Prev. maint.
High speed grinding	Time and cost
Grinding trolley	Time and cost
Panel replacement	Time and cost

Figure 35: Findings in V-representation, as according to EN 50126 and the link and effect model.

6.2. Recommendation

There is good scope of using the presented models and also the outcome of the models to drive maintenance decision making towards reduction of track possession time. In regard to the objectives of the AUTOMAIN project, the simulation and optimisation models for grinding, tamping and S&Cs, as presented this project can be suitably adapted for any track section after necessary modifications to suit the specific requirements of the IMs.

The identified best practices, improvement and innovations for the three maintenance activities under consideration suggested in D4.1 (improvement analysis of high performance maintenance) can be further studied for implementation so as to achieve the possible reduction shown by the different models. Another essential element in the successful implementation of the approaches/models presented is the quality and reliability of historical data of maintenance possession time and condition data of the track structure. The works done herein are as required by the objectives of AUTOMAIN, further work would be, development of prognostic health management programme for track with practical infrastructure prognosis models.

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Appendix A: Glossary

Maintenance:	is the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function.
Performance killer:	is an input element to an organization, which hinders and results in poor performance of the process or business.
Performance driver:	is a supporting input element to a process, which drives and enhances the performance of the process or business.
Cost driver	is an input element to a process, which drives and affects the costs.
Link and Effect Model:	The link and effect model is a methodology for developing performance measurements systems, by combining performance measurement and engineering principles for proactive management of physical assets.
Strategic planning	can be described as the process of specifying objectives, generating s trategies, and evaluating and monitor results (Armstrong 1982).
Strategy:	Courses of action that will lead in the direction of achieving objectives.
Key Result Area (KRA):	Areas where results are visualized with an organization.
Critical Success Factor (CSF):	Are those characteristics, conditions, or variables that when properly managed can have a significant impact on the success of an organization.
Performance Indicators (PIs):	Parameters (measurable factor) useful for determining the degree to which an organization has achieved its goals (U.S. Dept of Energy 1993), or numerical or quantitative indicators that show how well each objective is being met (Pritchard et al. 1990.
Key Performance Indicator (KPI):	The actual indicators used to quantitatively assess performance against the CSFs (Sinclair et al. 1995). A KPI is a PI of special importance comprising individual or aggregated measures.

Appendix B: Performance killers of tamping, grinding and S&Cs

The inputs from WP1 and WP2 are considered under WP 4 for performance killers. The performance killers are considered and analyzed for their relationship with the innovation, categorization, issues and possibilities of usage/application. Tables 1-3 in Chapter 1 is according to the table below.

Grinding

Issue	affecting our task			Potential		comments	Priority			Priority_no
	high	medium	low	high	low		high	med	low	0/1/2
1	3			3					1	7
2						we have to identify the reasons for this				0
3						we have to identify the reasons for this				0
4	3			3		comments about this issue in the report		2		8
5						out of project scope, corrective maintenance				0
6						we need more information about this				0
7						we need more information about this				0
8	3			3		this is not a performance killer			1	7
9						out of project scope, corrective maintenance				0
10										0
11						out of project scope				0
12	3			3		comments about this issue in the report		2		8
13						out of project scope				0
14						we need more information about this				0
15						culture, out of project scope				0
16						we need more information about this				0
17						?				0
18						Willem will look for quantities				0
19						out of project scope, corrective maintenance				0

20	3			3			3			9
21						culture, out of project scope				0
22						logistic process, out of scope				0
23			1		1	comments about this issue in the report		2		4
24			1		1	related to process and data analysis			1	3
25						out of scope of project				0

Tamping

Issue	affecting our task			Potential		comments	Priority			Priority	*Priority*	*Issue*	*Categorie*	*Strukton comments*			
	high	med	low	high	low		high	med	low				*Possession*	*42-50% Tamping 17-21% Transport 6-15% Confirm. 1-10% Comm. 7-25% Waiting*	Improvement	Innovation	FR
1,7	3			3		relevant	3			9	*7-25% Waiting P9*	*1,7.low utilisation of possession time, and often a low level of confidence which prompts high levels of contingency time to be planned in*	*Planning*	*Plan optimum production depends lifting height and insertations*	max. 25% poss time		FR05
1,8	3			3			3			9	*7-25% Waiting P9*	*1,8.The time spent waiting for the machine to warm up*	*Machine*	*Best practice: Start machine 1 hour before possesion and do input and safety instruction etc.*	max. 25% poss time		FR05
2,1	3			3		connencted to 1,8	3			9	*17-21% Transport P9*	*2,1.Distance between the machine stabling point and the worksite*	*Infra*	*Infra related not easy to change NL switch every 20km=30min.*	max. 21% poss time		FR10
3,5	3			3		for better planning of maintenance tasks	3			9		*3,5.Lowe knowledge of degradation, it is unclear how far track should be allowed to deteriorate and what rate should trig a special maintenance activity*	*Infra*	*See Standards EN13231 EN13848 EN15341*			
3,8	3			3		connencted to 3,5	3			9		*3,8.there is insufficient understanding of the optimum point at which to plan intervention*	*Planning*	*see attention values of Line categories*		Optimise Tamp strategy	

4,2	3			3			3			9		*4,2.Lack of standardisation regarding key tamping parameters such as the optimum speed of tamping, the pressure to be applied to the tamping tines, and the depth at which they are inserted. It was suggested that there is a need for better guidance on the optimum approach.*	*Operators*	*Better training*			
4,4	3			3		performance driver, connected to 3,5	3			9		*4,4.No good tools for analysing of existing track recording data to trend deterioration rats*	*Planning*	*Develop software*		New Software	
6,8	(x)			(x)		related to UK, best practise	3			9	*1-10% Comm. P9*	*6,8.Machine safety checks and briefings should be undertaken prior to arriving at site if at all possible*	*Possession*	*Best practice: Start machine 1 hour before possesion and do input and safety instruction etc.*	max. 10% poss time		FR05
4,5	3			3		universal high performance machine		2		8	*42-50% Tamping P9*	*4,5.Limited flexibility and highly variable capability between machine types*	*Possession*	*Best practice High speed liner 09-4X = 2000m/h 09/3x 1500m/h 09/32 1000m/h 09/16 500m/h or Universal 09-32-4s = 1100m/h*	max. 50% poss time	Choose corect Tamper USM or Highperformance Tamper	FR05
6,1	3			3		related to the obejectives of AutoMain		2		8		*6,1.Tamping Slow mowing in between scheduled service trains*	*NO* Possession	*Tamping in between trains Production decreases 1hour for leaving the track and efficiency -50% depends train interval*	Price of Poss. time / Prod. Efficiency ?	Time charing the track with controled asses	
6,3	3			3				2		8		*6,3.the other work activities going on at the same work site are interfering*	*Finance*	*Combined projects because Penalty on track possesion*			

1,1	3				1	technical solutions could increase potential, but not in scope of project			1	7	*6-15% Confirm. P9*	*1,1.Safety regulations, many of the non value added activities was related to safety*	*Possession*	*Safety very important but can be more efficient*	max. 15% poss time	ZKL3000 = Remote control Track Circuit Operating Device http://www.dualinventive.eu/en/services#zkl-3000	FR05
1,5	x					planning of individual tamping performance (09-32, 09-4x ..) will show higher potentials, but not in scope of project			1	7		*1,5.interference to the planning processes from a multitude of unplanned events such as changes in policy, budgets, availability of machinery or other high priority maintenance work for example*	*Planning*	*better budget Planning*			
2,3	3				3	fixed point measurements by track recording car could reduce possesion time			1	7	*9% Record run P9*	*2,3.undertaking a recording run prior to maintenance. Inspection data is missing, do not know the track Q*	*Possession*	*Recording car conversion Compensation method Pallas system Fix point*	max. 9% poss time	Fix point measure car V100 or Inertial mesure on Tamper V100	FR05
2,4	3				3	reliability of tamping machine			1	7		*2,4.Number of shifts cancelled or curtailed due shortage of appropriated staff*	*Operators*	*Training*			
3,1		2			3	part of project		2		7		*3,1.No International exchange of experiences*	*Operators*	*Strukton Operators work in NL-Ge-Be-Skandinavia*			
3,4	3				3	for UK			1	7		*3,4.Significant proportion of tamping actually makes track quality worse (as much as 25%).*	*Infra*	*Reserch and discussion*			
3,6	3				3	not in scope of project			1	7		*3,6.Maintenance budget and tamping targets - is not always aligned*	*Finance*	*see Contract*			

3,7	3			3		not in scope of project			1	7		3,7.targets are frequently set according only to the length of track to be tamped, which tends to result in inefficient and ineffective maintenance planning	Planning	Plan optimum production			FR05
6,7	3			3		high potentials especially for grinding, recommen dations			1	7		6,7.The requirements for stabling for maintenance machinery need to be considered by and incorporated into route utilisation strategies if it is not already done so.	Infra	Infra related not easy to change NL switch every 20km=30min.	max. 21% poss time		FR10
4,7	3			3		project should think about this issue				6		4,7.Winter, warm days					
4,8	(x)			(x)		UK issue, best practise				6		4,8.time spent travelling to and traversing the work site (an issue likely to get worse given the tendency to remove switches an sidings), and other aspects related to the abilities of the equipment used.	Infra	Infra related not easy to change NL switch every 20km=30min.	max. 21% poss time		FR10
5,5	3			3		recommen dation				6		5,5.a whole life cost / benefit model or case study for an advanced tamper design should be undertaken = recommendation , not a killer	Machine	Best buy Usm /Special machine Strukton is very interested			
5,6	3			3		recommen dation, related to 2,3				6		5,6.Alternatively, track recording equipment could be installed on service vehicles, or on the tamper itself, traversing the worksite at some point prior to the maintenance possession. The development of so called "Geotag" systems which automatically transfer data to the tamper in preparation for maintenance	Machine	Conversion needed from Recording car to Tamper		Softwa re	FR05

												was also mentioned = recommendation					
1,2			1	3		planning			1	5		*1,2. the planning of track maintenance involves a complex and lengthy process, involving multiple departments with long lead times*	*Planning*				
2,2			1	3		connencted to 1,2			1	5		*2,2.Multiple departments with long lead time*	*Planning*				
3,2	3				1				1	5		*3,2.Lack of operators*	*Operators*	*Training*			
5,7		2			1			2		5		*5,7.Validate the results of different methods for tamping amongst them stoneblowing = Rec.*	*Infra*	*Reserch and discussion*			
2,7		2			1				1	4		*2,7.there is low visibility of skill level requirements or status within maintenance crews, and low visibility of optimum training requirements*	*Operators*	*Training*			
5,8		2			1	between possesions related to safety regulations			1	4	*17-21% Transport P9*	*5,8.Limited speed of the tamper when travelling to and from the work site*	*Possession*	*Safety speed limited 40kmh Keep line open till arrival 80kmh*	max. 21% poss time		FR05 FR10
6,5		2			1				1	4		*6,5.a low level of standardisation in terms of infrastructure design*	*Infra*	*sleeper distance comes with difference axle load Class A B C D distance 09-3X 58-62cm*			

1,3			1		1				1	3		1,3.This hinders the flow of information, which in turn delays the decision making process and creates waste within the value chain	Planning				
1,4			1		1				1	3		1,4.the planning processes lacks standardisation	Planning				
1,6			1		1				1	3		1,6.multiple re-work loops due to low levels of information and long time frames	Planning				
2,5			1		1				1	3		2,5.the effectiveness of the plans can be hindered by the degree of variation in delivery rates between different machine operators	Operators	Training			
2,6			1		1				1	3		2,6.there were instances where the scheduling of manpower resulted in high value machinery standing idle during possessions, and other instances where appropriately skilled staff were not available at the required time	Operators	Training			
5,1			1		1	recommendation			1	3		5,1.Whether or not the machine can record in one direction and then immediately start tamping in the other (some designs can only measure and work in a single direction)	Machine	DB Unimat sprinter can NL. Not allowed to run back on open line			
5,3			1		1	recommendation			1	3		5,3.machines that could warm up while travelling to work sites = Recommendation not a killer	Machine	**Best practice:** Start machine 1 hour before possesion and do input and safety instruction etc.	max. 25% poss time		FR05
5,4			1		1	recommendation			1	3		5,4.Drive on and off the track – innovation, not a killer	Machine	Minima can stabele beside track but is not a Highperformance Tamper	max. 21% poss time		FR10

5,9			1		1	conflicts with maintenance cost			1	3		*5,9.Low availability of track crossovers, which frequently result in long distances being travelled to get machines to the work site*	*Infra*	*Infra related not easy to change NL switch every 20km*	max. 21% poss time		FR10
6,4			1		1				1	3		*6,4.the machine arrives at the work site facing in the wrong direction to start work immediately*	*Planning*	*Workdirection in tranport plan*			
3,3						connected to 1,1				0		*3,3.Not possible enabling adjacent lines to remain open to bi-directional traffic during maintenance.*	*Infra*	*Safety very important but can be more efficient*			
3,9						not a performance killer than recommendation				0		*3,9.No realistic maintenance targets*	*Planning*				
3,10						not a performance killer than recommendation				0		*3,10.Not targeted approach, based on increased use of track geometry and condition data.*	*Planning*				
4,1						not a performance killer than recommendation				0		*4,1.Safety limits are used instead of maintenance limits*	*Planning*				
4,3						?				0		*4,3.Lack of way side monitoring equipment for detecting and rectifying faults quickly*	*Machine*	*cameras*			
4,6						connected to 4,5				0		*4,6.The suitability of tamping machine designated for a given location / possession was frequently less than optimal*	*Machine*	***Best practice*** *High speed liner 09-4X = 2000m/h 09/3x 1500m/h 90/2x 1000m/h 99/1x 500m/h or Universal 09-32-4s = 1100m/h*	max. 50% poss time	Choose corect Tamper USM or Highperformance Tamper	FR05
4,9						connected to 2,3				0		*4,9.The time required to input track geometry data into the machine's control system*	*Machine*	***Best practice:*** *Start machine 1 hour before possesion and do input and safety instruction etc.*	max. 25% poss time		FR05
5,2						connected to 5,1				0		*5,2.Tampers not capable of recording and tamping in either direction.*	*Machine*	*Machine wil be twice expencive to solve a Transport problem ?*			

6,2						related to 1,5				0		*6,2.Need for adoption of Standard Operating Procedures*	*Operators*	*Training*			
6,6						related to 6,5				0		*6,6.greater standardisation, ensuring that track always has consistent sleeper spacing*	*Infra*	*sleeper distance comes with difference axle load Class A B C D distance 09-3X 58-62cm*			