AUTOMAIN

Augmented **U**sage of **T**rack by **O**ptimisation of **M**aintenance, **A**llocation and **I**nspection of Railway **N**etworks

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D1.3: Evaluation of performance impact of AUTOMAIN solutions.

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Document Summary Sheet

After defining its objectives and requirements in deliverables D1.1. and D1.2, the AUTOMAIN program chose to evaluate its results at the finalisation of the program. In this report the AUTOMAIN results are matched to the original ideas and objectives. It describes to what extent the objectives have been met and where activities did not bring what had been intended.

Apart from the formal AUTOMAIN objectives, some conclusions and recommendations are formulated regarding the program set-up and organisation.

This document is the report covering deliverable D1.3.

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V13	31 Jan 14	Final	All changes accepted. Minor changes to the conclusion chapter. Summary added. This version has been uploaded to the commission.

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Summary

From February 2011 till the end of January 2014, the AUTOMAIN consortium worked on innovations and improvements to reduce the possession time on railway networks necessary for maintenance by 40%. By initiating and executing research in the field of inspection, high performance maintenance, modularisation and planning, novel ideas and techniques have been developed to support the desired improvement. The application of lean analysis techniques, as used frequently in other industries, was also part of the research within the program.

The AUTOMAIN program has been set up according to the system engineering principles. These principles led to a definition of work packages. But is also supported a clear description of objectives and requirements in an early stage of the program. Based on the SE set-up an evaluation of the result has been executed in the final stage of the program. The aim of the evaluation is to find out to what extent the original objectives have been met. This report contains the evaluation of AUTOMAIN.

Overall the AUTOMAIN consortium concludes that the work done shows clearly that the intended improvement of 40% reduction of possession time is feasible. Eventually it formulated fifteen conclusions and recommendations:

Conclusions

1. The AUTOMAIN program shows to have reached its quantitative objectives. In total the developments and innovations within the program indicate that a possession time reduction between 33 and 41% is achievable.
2. The goal of objective 1 has been met by applying lean analysis techniques in a railway maintenance environment and showing that on the long term possession for key tasks be reduced by 43-47%.
3. Possession time for inspection can be reduced by over 60% by applying the developed techniques such as overhead cameras, train-borne S&C inspections and hand-held inspection devices.
4. Large scale maintenance tasks can be optimised by applying some of the developed innovative approaches such as combining grinding machines, fast slag collection and high speed grinding combined with conventional grinding, leading to a reduction in possession time up to 41%.
5. Modularisation of creates interesting design options such as the movable blade, although in this stage of the developments it is not possible to estimate the effect on possession times.
6. Applying novel algorithms and planning techniques shows a possibility to reduce maintenance possession times by almost 15% simultaneously optimising travelling times of machinery and costs.
7. The eventual results and their achievability depend strongly on (1) the national maintenance strategy, (2) the developments in work organisation that have been realised earlier and (3) the success of necessary future technical developments.

8. The exchange of knowledge between partners should be considered as part of the innovation process. Existing technology in one country turned out to be the innovation in another. For that reason some of the innovations mentioned by the WPs could be considered existing technology and therefore, not really innovative: for example, high speed tampers and grinders. The innovative part in the research often covered the application of those existing technologies and the disclosure of their benefits in a clear defined way.

Recommendations

9. Railway managers as well as other involved companies are advised to consider in what way the AUTOMAIN results can be made applicable in their situation. Only then the real results can be booked.
10. The field of data management and exchange of data is recommended as interesting for further research. One obvious problem has been the availability of data on which to base the research. Obtaining a data set which is consistent across a range of IMs, which is consistent across a range of IMs, is a well-known problem. The university of Luleå already took the initiative to start further research on the topic of data management for maintenance (see §3.4.1).
11. The further development of RailML as a common standard for information exchange has been touched in AUTOMAIN but shows promising possibilities for future research.
12. The developed planning system shows interesting perspectives for further development. Some parties (including the University of Braunschweig) are already preparing further work based on the foundations built by AUTOMAIN.

We hope that our efforts will contribute to a growth in railway traffic and a further optimisations of maintenance activities. Good luck in applying our results in your situation. All detailed information can be found on www.automain.eu .

The AUTOMAIN consortium.

List of abbreviations and acronyms.

CR	Capability Requirement (a detailed list with CRs and FRs can be found in deliverable D1.1, §4.3)
DB	Deutsche Bahn A.G.
DoW	Description of Work, a document last changed on 8 November 2011 and sent in during the application phase as Annex I to the consortium's proposal.
DS	Demonstration Scenario, referred to as DS1 and DS2 (see Chapter 5).
Dx.y	AUTOMAIN deliverable number y from work package x, as defined in the DoW. For a complete list of deliverables refer to Appendix A.
EFRTC	European Federation of Railway Track Contractors (Luxembourg)
FR	Functional Requirement (a detailed list with CRs and FRs can be found in deliverable D1.1, §4.3)
HSG	High speed grinding
IM	Infrastructure Manager
KPI	Key Performance Indicator
LTPP	Long-Term Planning Problem, also referred to as problem 3.
LTU	Luleå Tekniska Universitet (Sweden)
NR	Network Rail Infrastructure limited
PI	Performance Indicator
PR	ProRail b.v. (The Netherlands)
S&C	Switches and crossings.
SE	System Engineering
SNCF	Societé Nationale des Chemins des Fer (France)
Tx.y	AUTOMAIN task y from work package x, as defined in the DoW. For a complete list of deliverables refer to Appendix A.
TRL	Technology Readiness Level, defined as: TRL 1 Basic principles observed and reported TRL 2 Technology concept and/or application formulated TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept TRL 4 Component validation in a laboratory environment TRL 5 Component validation in a railway environment TRL 6 System/subsystem model or prototype demonstration in a railway environment TRL 7 System prototype demonstration in a railway environment TRL 8 Actual system completed and qualified through test and demonstration TRL 9 Actual system proven through successful mission operations
TUB	Technische Universität Braunschweig (Germany)
TWIP	Time Window Insertion Problem, also referred to as problem 1.
UIC	International Association of Railways – Union Internationale des Chemins des Fer (France)
UNIFE	Association of the European Railway Industry (Belgium)
UoB	University of Birmingham
VSM	Value Stream Mapping, one of the applied lean techniques.
WP	Work Package
WSSP	Work Site Scheduling Problem, also referred to as problem 2.

1. Introduction to AUTOMAIN and this report.

1.1. AUTOMAIN.

Freight shippers are finding it increasingly difficult to get the train paths they need on the European railway network. Increased passenger demand has reduced the number of opportunities available to run freight trains during the day. It has also forced infrastructure managers (IM) to concentrate maintenance work in the night-time hours, when passenger traffic is low. The result is a reduction in the overall availability of freight paths.

The AUTOMAIN project aims to reverse this trend, by improving the efficiency of track maintenance to reduce the amount of time the railway is closed to traffic. This will be achieved through the development of innovative technologies and procedures in a number of areas, including: analysis and optimisation of maintenance processes; higher speed infrastructure inspection; higher speed track maintenance; modular infrastructure components and sub-systems, and; automatic maintenance scheduling and planning systems.

AUTOMAIN takes a four concepts approach to increasing the availability of freight train-paths. The first step change (from concept 1 to 2 in Figure 1) aims at reducing current night-time maintenance track closures through the application of best-practice maintenance technologies and procedures. The second step change (from concept 2 to 3) investigates the development of innovative techniques to facilitate maintenance during the day, in short possessions between trains.

Finally, the third step change (from concept 3 to 4) explores the development of radically new techniques and procedures to facilitate maintenance at line speed. The fifth concept shown in Figure 1, covers the maintenance-free railway, and is outside AUTOMAIN's scope of work; however, it is likely that AUTOMAIN's research will contribute to future research projects aimed at achieving concept 5.

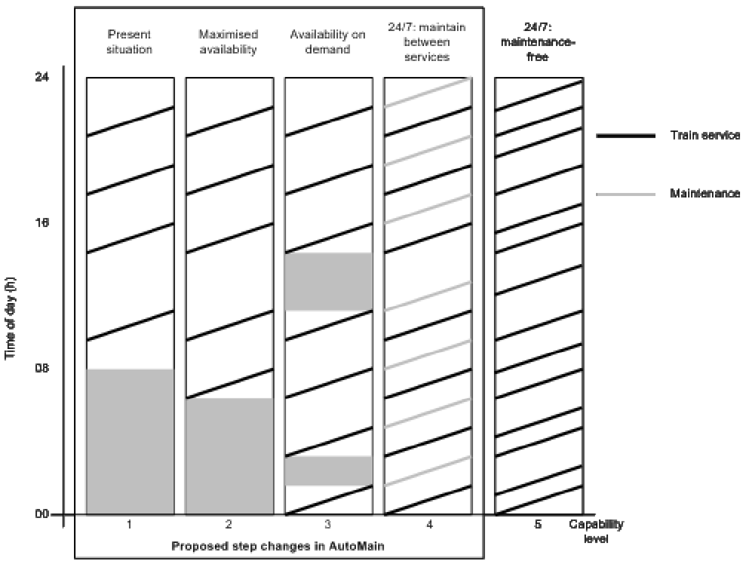

Figure 1; The five operating concepts defining the AUTOMAIN research objectives.

In order to assure that the whole project eventually leads to the intended results, AUTOMAIN has organised itself according to the system engineering (SE) principles (see Figure 2). These principles include the definition of requirements in an early stage of the project. In the same stage, the ways to validate and evaluate the results have to be defined.

AUTOMAIN also aims at initiating some innovations. These innovations will be used to support the step changes. In the DoW the following innovations are mentioned:

1. A new methodology for analysing and optimising maintenance processes by applying best practice from other industries;
2. Higher speed infrastructure inspection methods;
3. Higher speed track maintenance methods;
4. Modular infrastructure components and subsystems which lend themselves to automated removal and fitment;
5. The improvement of automatic maintenance scheduling and planning systems, which focus on scheduling maintenance around the timetable, so as to reduce disruption to scheduled traffic and to increase useful capacity.

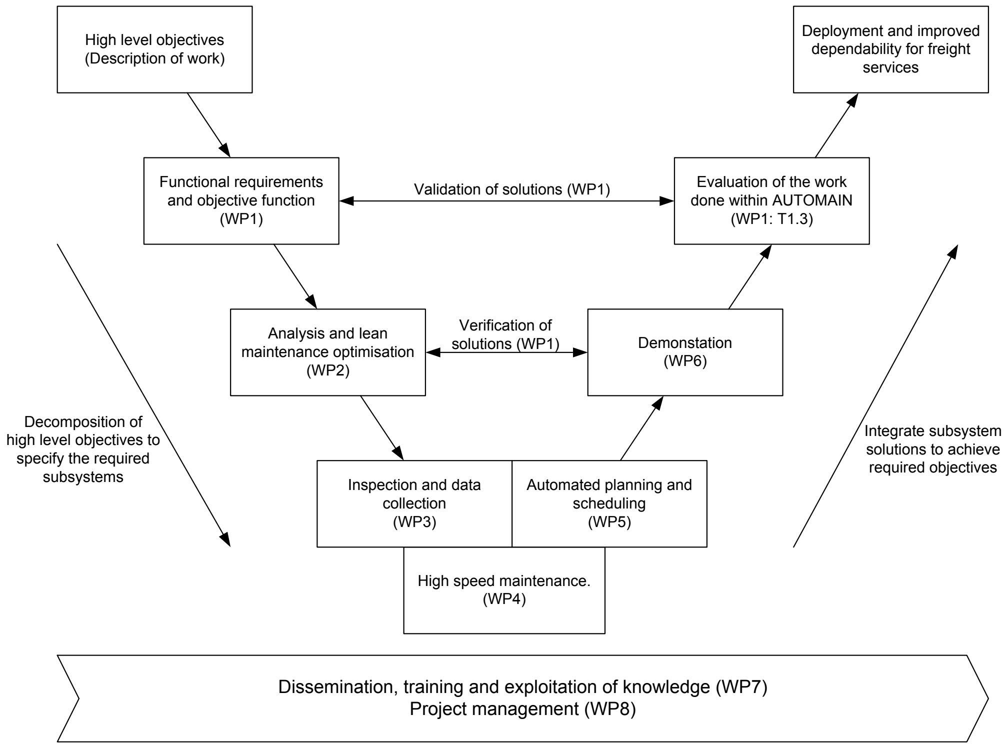

Figure 2; The SE-structure as used within AUTOMAIN.

1.2. Explanation of the evaluation process.

Based on the SE-approach of the AUTOMAIN program, a program evaluation has been done in the final stage of the program. The results of that evaluation can be found in this report. The idea of this evaluation is to summarise:

- If the original objectives have been met.
- If all results together lead to an improvement on the 'system-level'.

In order to do this, a process had been developed. In that process WP-leaders summarised their results in so called data-sheets. These sheets contain the main objectives and targets of the WP. The authors of this report based it on the information in these sheets. They did not read and interpret the separate deliverables.

As a result this report will frequently refer to deliverable reports, in which more detailed information is available. For an overview of the deliverables please refer to Appendix A.

1.3. Introduction to this report.

This report intends to evaluate the whole AUTOMAIN-program. In deliverable D1.2[1] the consortium described its objectives and evaluation criteria. That report D1.2 has been written in order to have the criteria available in an early stage of the program. In this evaluation report we will continuously refer to the D1.2 criteria. Most of the tables containing evaluation criteria (e.g. Table E) are directly copied from D1.2.

This report starts with an evaluation of the program's objectives in chapter 2. The quantitative results of the WPs are gathered and presented. Based on these numbers an attempt is made to calculate the overall result of AUTOMAIN.

In chapter 3 a listing is made of the innovative results of all WPs. This is done according to the five innovations that AUTOMAIN aimed at initiating. For the evaluation of the objectives and the innovations not all WPs are equally relevant. In Appendix B an overview is given of the relations between WPs, objectives and innovations.

The results of the development of a planning tool (WP5) are discussed in chapter 4.

In chapter 5, special attention is given to the results of the demonstrators (WP6). From the SE-way of setting up the program, WP6 contains an effort to combine all results and conclude about the total effect.

In an early stage of the program (deliverable D1.1 d.d. October 31th, 2011) an elaborate list of functional and capability requirements was defined. In chapter 6 the results in terms of these requirements are summed up.

Eventually in the chapter 7 we wrap up all results and lessons learned by formulating some evaluation remarks as well as a list of conclusions and recommendation.

[1] "Deliverable D1.2: Description of demonstration scenarios and evaluation criteria." Submitted to the commission on January 31th, 2012. Also available on www.automain.eu .

2. Objectives and results.

2.1. KPIs: the definitions.

In deliverable report D1.2 more explanation has been given concerning the objectives. In that report the objectives are (based on the information from the DoW) linked to the defined work packages. This led to the schema in Figure 3.

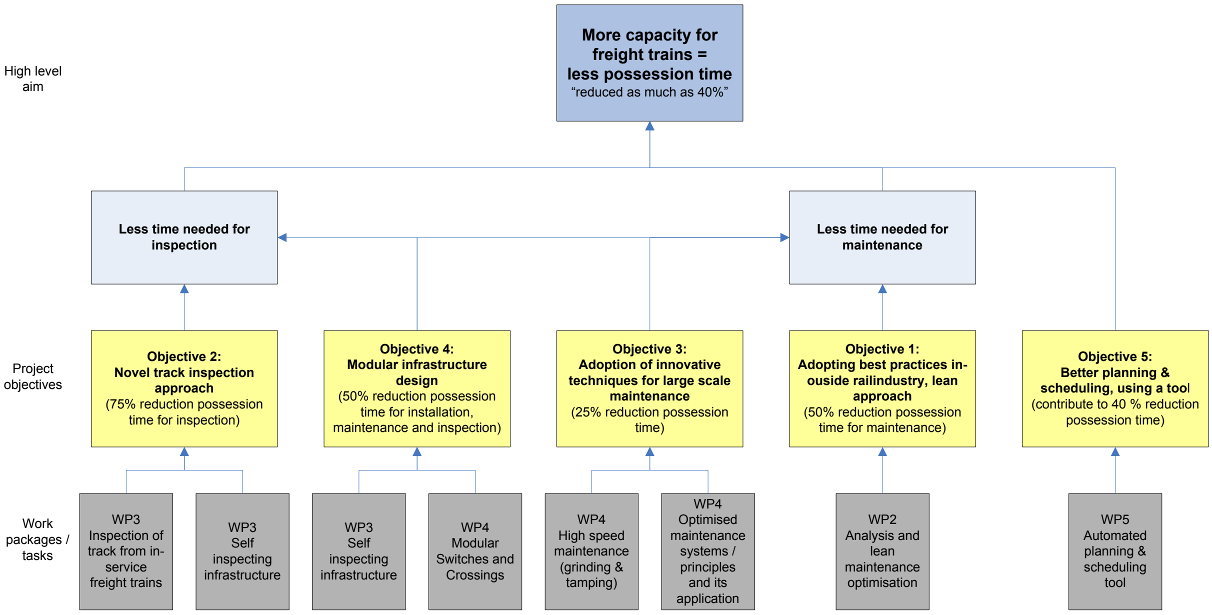

Figure 3; An overview of the AUTOMAIN objectives and work packages and their interrelations.

In order to refine the objectives some further investigation has been done. This made clear that the objective per WP essentially depends on the distribution of the possession times over the different categories.

The DoW refers to 5 categories of work without further definitions. As a first step all categories have been defined more specifically:

- maintenance (key tasks): "normal" maintenance activities that need possession periods of at least 5 hours.
- maintenance: "normal" maintenance activities that can be executed in possession periods of less than 5 hours.
- large scale maintenance (key tasks): maintenance tasks for which large machinery has to be used (tamping, grinding, etc.) that require possession periods of at least 5 hours.
- large scale maintenance: maintenance tasks for which large machinery has to be used (tamping, grinding, etc.) and can be executed in periods of less than 5 hours.
- Inspection: all inspection and monitoring work.

In Table A the relation is shown between the maintenance category and the objectives. In this stage a decision was taken to separate objective 4 (the development of modular infrastructure design) from the others, because it does not relate to the current distribution of possessions, but will have an effect in the future. For that reason the impact of objective 4 will have to be estimated separately in the relevant WPs.

Maintenance task	**Objective 1 Adopting best practices**	**Objective 2 Novel track inspection**	**Objective 3 Innovation in large scale maintenance**	**Objective 5 Better planning & scheduling**
maintenance (key tasks)	X			X
maintenance				X
large scale maintenance (key tasks)	X		X	X
large scale maintenance			X	X
inspection		X		X

Table A; Relation between objectives and maintenance tasks. [2]

An estimate has been made of the distribution of possession times over the maintenance task categories. This was not a simple job, as most of the IMs and maintenance contractors do not use these categories in their registration. The estimate, based on the known numbers in the Netherlands, is shown in Table B.

task	**actual hours**	**[%]**
maintenance (key tasks)	483,2 hrs	18%
maintenance	1249,5 hrs	46%
large scale maintenance (key tasks)	322,1 hrs	12%
large scale maintenance	138,8 hrs	5%
inspection	500,0 hrs	19%
		100%

Table B; Estimated distribution of possession times based on data from The Netherlands.

It should be noted that the assessment of this distribution is fundamental for the eventual overall results: e.g., if the percentage of possessions for inspection was reduced, this would affect the ability of extent objective 2 to contribute to the overall target reduction in possession time and increase the contribution required from the other objectives. That's why a vulnerability check will be done and a calculation sheet will be made available to check the effects of other distributions. In this way newer insights or new data can be incorporated to refine the results further.

Finally all reductions were put in a calculation sheet[3]. It was assumed that the objectives will be effective consecutively. This means that objective 5 is the final objective and will have an effect on

[2] The application of the objective to the different tasks is based on what has been defined in the DoW: e.g. objective 1 has been aimed at the key tasks according to the DoW where an application to the other tasks may as well be useful.

all categories in order to achieve the ultimate goal of 40%. The results of these calculations are a more precise effective reduction percentage for each objective.

Based on the estimated distributions of possession times in the Netherlands the effect of the innovations is shown in Table C.

	Annual possession time (the Netherlands)		Objective 1 Adopting best practices	Objective 2 Novel track inspection	Objective 3 Innovation in large scale maintenance	Objective 5 Better planning & scheduling
Reduction (according to DoW)			*50% for key maintenance tasks.*	*75% for inspection*	*25% for large scale maintenance*	*resulting in 40% overall effect*
Maintenance task	actual hours	[%]	[%]	[%]	[%]	[%]
maintenance (key tasks)	483,2 hrs	18%	9%	9%	9%	8%
maintenance	1249,5 hrs	46%	46%	46%	46%	41%
large scale maintenance (key tasks)	322,1 hrs	12%	6%	6%	4%	4%
large scale maintenance	138,8 hrs	5%	5%	5%	4%	3%
inspection	500,0 hrs	19%	19%	5%	5%	4%
Total		100%	85%	71%	68%	60%
Effective overall reduction		-	**15%**	**14%**	**3%**	**8%**

Table C; Calculation of the overall effect of the different AUTOMAIN objectives.

__Explanation of the calculations:__

Based on annual maintenance hours data for the Netherlands, the total hours and percentage of total hours for the five maintenance categories considered by AUTOMAIN are shown in the left hand column of the table. The other four columns show, for each objective, the reduced percentages necessary to achieve each of the AUTOMAIN research objective targets:

- *Objective 1 has the target of reducing maintenance hours for key maintenance tasks by 50%; The table shows hours for 'maintenance (key tasks)' and 'large scale maintenance (key tasks)' reduced by 50% compared to the left hand column, producing an overall reduction of 15% on total hours.*
- *Objective 2 seeks a 75% reduction on track inspection time. The table shows hours for 'inspection' reduced by 75% compared to the objective 1 column, producing an overall reduction of 14% on total hours compared to that achieved by Objective 1.*
- *Objective 3 seeks a 25% reduction on 'large scale maintenance' and 'large scale maintenance (key tasks)'. The table shows hours for 'large scale maintenance' and 'large scale maintenance (key tasks)' reduced by 25% compared to the objective 2 column, producing an overall reduction of 3% on total hours compared to that achieved by Objective 1 and 2.*
- *Automain's overall target is for a 40% reduction across all maintenance categories, but Objectives 1, 2 and 3 are already aiming to achieve a saving of 32% (= 15% + 14% + 3%). Therefore, the percentages in the Objective 3 column have been factored to obtain the overall 40% saving for Objective 5, which also results in an additional 8% saving compared to Objective 3.*

Summarizing the calculations give the following overall effect per objective:

- Adopting best practices: 15%
- Novel track inspection: 14%
- Innovation in large scale maintenance: 3%
- Better planning and scheduling: 8%

Two aspects are important enough to be mentioned separately:

[3] An Excel-sheet has been set up to facilitate these calculations. This sheet has been made available for partners on the program's website: www.automain.eu.

The possession time used for inspections differs very much between the involved countries. The Netherlands are known to have very strict safety regulations that do not even allow small inspections between trains. This fact causes a rather big amount of possessions used for inspections, where other countries (e.g. France) hardly use any possessions for inspection. Of course this difference will also affect the overall results of the calculations made in the report. A brief recalculation with reduced possession time for inspection shows (see Table D) a major effect in the resulting objectives for objectives 2 (to 0) and 5 (grows to 18%). This example illustrates that the AUTOMAIN results may differ per country and may also be strongly influenced by changing (safety) regulations.

	Annual possession time (the Netherlands)		Objective 1 Adopting best practices	Objective 2 Novel track inspection	Objective 3 Innovation in large scale maintenance	Objective 5 Better planning & scheduling
Reduction (according to DoW)			*50% for key maintenance tasks.*	*75% for inspection*	*25% for large scale maintenance*	*resulting in 40% overall effect*
Maintenance task	actual hours	[%]	[%]	[%]	[%]	[%]
maintenance (key tasks)	483,2 hrs	22%	11%	11%	11%	8%
maintenance	1249,5 hrs	57%	57%	57%	57%	44%
large scale maintenance (key tasks)	322,1 hrs	15%	7%	7%	6%	4%
large scale maintenance	138,8 hrs	6%	6%	6%	5%	4%
inspection	0,0 hrs	0%	0%	0%	0%	0%
Total		100%	82%	82%	78%	60%
Effective overall reduction		-	**18%**	**0%**	**3%**	**18%**

Table D; Recalculation with almost 0 possession time claimed for inspection.

Another issue concerns the IMs' policies on maintenance and inspections. Actually in Germany a rather low capacity is claimed for monitoring purposes. Nevertheless DB aims at enlarging the amount of preventative maintenance and by doing so, improving the predictability of the work to be done. This leads to a growing need for monitoring results that drives innovations as used in AUTOMAIN to inspect the infrastructure using regular trains. The results of AUTOMAIN in Germany will therefore not be significant in reducing the possession time for inspections but in making more possible without claiming extra slots. The results will merely facilitate the need for information to improve the effectiveness of maintenance without increasing the claim on track capacity.

2.2. Realized reduction of possession time

The results from the work packages in terms of their effect on the objectives are shown in this section.

2.2.1. Objective 1: Adopting best practices in/outside rail industry, lean approach (50% reduction possession time for maintenance[4])

The information to evaluate objective 1 has been gathered from WP2 (D2.1 and D2.2) as well as WP4. Although this had not been planned initially, WP4 took an effort to use lean analysis methods to find the main fields of potential improvement in grinding and maintenance of switches and crossing.

Relevant KPI	
KPI_1 = (1 – possession time required for maintenance using innovation / actual required possession time for maintenance) x100%. **Objective**: the benchmark possession time for key maintenance tasks can be reduced by up to 50%.	The WP shall calculate the expected gain in possession time by applying lean analysis methods. The elements used in this calculation (measured results, estimations, assumptions and extrapolations) shall be identified and quantified. The main elements that lead to the expected progress will be mentioned.

Table E; Reference information for KPI_1 (Source: D1.2).

General remark

The application of lean analyses in railway situations is regarded as the best practice from other industries. However, an analysis shows the potential gain, it does not improve anything. The numbers shown in this objective should therefore be considered as the "state of the art" situation, showing potential improvement areas.

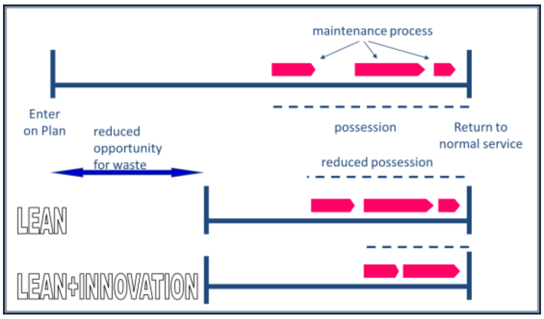

Figure 4; Schematic overview indicating the different effect of lean and innovation.

Moreover, the lean analysis focuses on the total process improvements that can be achieved. It does not focus on the actual technical activity (such as tamping or grinding itself). That area could be improved by developing innovations. Figure 4 shows the combined effect of both elements (lean and innovation). In chapter 3 detailed information about the developed innovation can be found.

Tamping:

The mean time used for tamping during a possession was 42% leaving scope within the remaining 58% of the possession for improvement. D2.2 found that causes of lost time were:

- Confirmation 6 to 15%
- Waiting 7 to 25%
- Communications 1 to 10%

[4] Maintenance (key tasks) and large scale maintenance (key tasks)

- Transport 17 to 21%

Using innovation to reduce these losses to an absolute minimum resulted in a target unavoidable loss of 6%.

$\mathbf{KPI_{1tamping}}$ = (1 – possession time required for maintenance using innovation / actual required possession time for maintenance) x100%.

$\mathbf{KPI_{1tamping}}$ = (1- (0.42 + 0.06)/1) x 100%. where 0.06 is the target unavoidable loss time (for transport and communications/confirmation)

$\mathbf{KPI_{1tamping}}$ = 52%

This assumes the following improvements that are not regularly achieved:

- No late possession starts
- Transport, communications and confirmation losses no more than 20 minutes of total possession time
- Tamper has prerecorded track geometry data (note: pre measurements need an additional shift!)
- No conflicting activities that prohibit tamper operation within the possession
- Machine and crew are the optimum combination for the conditions
- No unused contingency built into possession planning

LEAN analysis also identified necessary innovation that could lead to improvements to achieve the full 73% improvement if justified on a whole system LCC basis.

Note: To achieve the 52% reduction the LEAN analysis has to take into account the real alternating boundary conditions. The required maintenance has to be carried out and the risk increases dramatically if you have no time space.

Grinding:

As observed, the grinding and necessary supporting but non-value added activities accounted for 69% of the available possession. Leaving an additional 31% (or 45% improvement) that could be achieved from a continuous high speed grinding regime.

This lost time as a percentage of total possession time less contingency:

- Transportation 20%
    - 8% of this transportation time is transport between work sites and should not be targeted for reduction, as the consequence could be grinding rail between work sites that does not require grinding and does not therefore add value
- Waiting and machine problems 11%

Eradication of machine problems and waiting time would reduce the possession time by 11%.

After using innovation the required possession time is 0.71 (0.44 (actual grinding duration) + 0.08 (briefing and machine setup) + 0.08 (transportation between grinding locations) + .11 (post grinding quality check and set to transport mode)).

KPI_1 = (1 – possession time required for maintenance using innovation / actual required possession time for maintenance) x100%

$KPI_{1grinding}$ = (1 – 0.71/1) x 100% = 29%

Combined results

The combined result for tamping and grinding depends upon the annual possession times for each activity. Over the past decade the possession time for grinding relative to tamping has fallen as the understanding of the location and needs for preventive grinding activities and the use of high strength steel rails in critical locations has improved. The combined result has been calculated for tamping to grinding ratios of 3:2 and 4:1 in order to determine the sensitivity for the combined result:

$KPI_{1combined}$ = ($KPI_{1tamping}$) x Relative possession time tamping + ($KPI_{1grinding}$) x Relative possession time grinding

$KPI_{1combined\ (3:2)}$ = ((52% x 3) + (29% x 2)) / 5 = 43%

$KPI_{1combined\ (4:1)}$ = ((52% x 4) + (29% x 1)) / 5 = 47%

An optimal grinding strategy should not lead to a lower KPI or the KPI is wrong. Therefore a high speed grinding strategy that moves on from location to location without unnecessary rail grinding between locations should not have a KPI downgraded by this travelling time. Provided that the grinding strategy does not interfere with normal services we have an optimal solution.

2.2.2. Objective 2: Novel track inspection approach (75% reduction possession time for inspection).

The information to evaluate objective 1 has been gathered from WP3, including the demonstrations in WP6.

Relevant KPI	
KPI_2 = (1 – possession time required for inspection using the novel approach/ actual required possession time for inspection) x100% **Objective**: the benchmark for possession time for track inspection can be reduced by up to 75%.	The WP shall calculate the expected gain in possession time by applying inspection of track from in-service freight trains and introducing self-inspecting equipment. The elements used in this calculation (measured results, estimations, assumptions and extrapolations) shall be identified and quantified. The main elements that lead to the expected progress will be mentioned.

Table F; Reference information for KPI_2 (Source: D1.2).

For switch inspection, there are many factors which affect the ability to predict the impact of the advances made as part of the AUTOMAIN project including the country and inspection standards, type of switch, the condition of it; experience of the worker and so forth. However, the numbers documented below are an attempt to provide realistic view of the impact that they will have based on heavily used S&C found on mainlines and in the vicinity of busy stations and junction areas.

The initial research carried out by the University of Birmingham identified five broad S&C inspection areas, namely:

- Visual inspection – overhead camera
- Geometry measurement

- Profile, shape and position of S&C components
- Nondestructive testing (NDT) for cracks in rails
- Tightness and security of S&C components
- Point machine inspection

Details about these developments as far as they were in the scope of AUTOMAIN are given in §3.3 and chapter 5.

Overview

Table G shows an overview of the gain in possession time using the novel inspection techniques. The indicated possession times refer to the estimated time per switch, unlike the times given in Table B.

	Current possession time per S&C per annum (total minutes)[5]	New possession time per S&C per annum (total minutes)
Visual inspection	390	0
Geometry measurements	30	10 (hand-held); 0 (train-borne)
Profile shape and position	90	15 (hand-held); 0 (train-borne)
NDT testing	40	40
Tightness	60	0
Point machine	250	250
TOTAL:	**860**	**315 (hand-held); 290 (train-borne)**

Table G; Current possession time versus new possession time when considering proposed S&C inspection methods, excluding advances in NDT testing and point machine design.

A reduction in possession time **66%** can be achieved if (a) visual inspection is undertaken using overhead cameras, (b) geometry is assessed using train-borne measurement, (c) profiles of S&C are assessed using train-borne measurement, and (d) S&C uses smart washers and/or mechanically secured bolts.

A reduction in possession time **63%** can be achieved if (a) visual inspection is undertaken using overhead cameras, (b) geometry is assessed using hand-held measurement, (c) profiles of S&C are assessed using hand-held measurement, and (d) S&C uses smart washers and/or mechanically secured bolts.

Please note that (a) other miscellaneous inspection tasks such as checking drainage system were not considered as they were not part of any of the broad five S&C inspection areas and (b) no advances in NDT testing and point machine design were considered in this calculation (or indeed the project).

General remark

The monitoring of the track with in-service trains that was developed and tested in AUTOMAIN is a measurement activity which does not reduce or increase possession time. The monitoring does not replace the track inspection, which is necessary for safety issues, but delivers additional information for a more efficient planning of maintenance activities.

[5] A detailed explanation of the mentioned current possession times is given in § 3.3.1.

The effects of a more efficient and reliable planning and execution of the maintenance can't be estimated. The effects calculated above are estimations based on assumed inspections intervals and possessions. The effective possession time after applying these techniques depends strongly on the maintenance policy in the actual situation.

2.2.3. Objective 3: Adoption of innovative techniques for large scale maintenance (25% reduction possession time)

Relevant KPI	
KPI_3 = (1 – total possession time required for maintenance using innovative techniques/ actual required possession time for maintenance) x100% **Objective:** The project will undertake simulations to show how these technologies can reduce the benchmark possession time of large scale maintenance processes (e.g., grinding and tamping by up to 25%;	The WP shall calculate the expected gain in possession time by applying innovative techniques for large scale maintenance. The innovations include speed-improving measurements and optimised maintenance principles. The elements used in this calculation (measured results, estimations, assumptions and extrapolations) shall be identified and quantified. The main elements that lead to the expected progress will be mentioned. Remark: necessary elements to reach the same level as today's quality when practicing the innovation will have to be identified.

Table H; Reference information for KPI_3 (Source: D1.2).

Tamping

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 (See conclusion of D 4.2).

Grinding

The use of improved conventional grinding with 64 stones (considering reduced time for slag collection and reduced number of grinding passages) shows that reduction in track possession time in the order of 50% is achievable (see Table 8 of D4.2). HSG and twin HSG can also be used for the reduction of track possession time, in comparison with conventional grinding over 80% reduction in track possession time is feasible.

Similar to KPI_2 (WP2) the effect of grinding and tamping is combined (based on data WP2):

The combined result for tamping and grinding depends upon the annual possession times for each activity. Over the past decade the possession time for grinding relative to tamping has fallen as the understanding of the location and needs for preventive grinding activities and the use of high strength steel rails in critical locations has improved. The combined result has been calculated for tamping to grinding ratios of 3:2 and 4:1 in order to determine the sensitivity for the combined result

$KPI_{3\ combined}$ = ($KPI_{3\ tamping}$) x Relative possession time tamping + ($KPI_{3\ grinding}$) x Relative possession time grinding

$KPI_{3\ combined}$ (3:2) = ((((35% x 42%) / 48%) x 3) + (((50% x 71%) / 71%) x 2)) / 5 = 38%

$KPI_{3\ combined}$ (4:1) = ((((35% x 42%) / 48%) x 4) + (((50% x 71%) / 71%) x 1)) / 5 = 41%

2.2.4. Objective 4: Modular infrastructure design (50% reduction possession time).

The information to evaluate objective 4 has been gathered from WP3 and WP4.

Relevant KPI	
KPI_4 = (1 - possession time required after using modular elements/ actual required possession time) x100% **Objective**: the benchmark possession time for installation, maintenance and inspection during the life of the asset will be reduced by at least 50%;	The WP shall calculate the expected gain in possession time by applying self-inspecting equipment. The elements used in this calculation (measured results, estimations, assumptions and extrapolations) shall be identified and quantified. The main elements that lead to the expected progress will be mentioned. Remark: This should be exercised for inspection as well as for maintenance activities.

Table I; Reference information for KPI_4 (Source: D1.2).

Although several developments concerning the modularization of S&C are mentioned in §3.5, it turned out to be impossible to calculate the effect on the reduction of possession times.

2.2.5. Objective 5: Better planning & scheduling, using a tool (contribute to 40 % reduction possession time).

The information to evaluate objective 5 has been gathered from WP5 (D5.1 and D5.2).

Relevant KPI	
KPI_5 = (1 – possession time needed when using innovative scheduling tool/ actual needed possession time) x100%. **Objective:** The tool, together with the other individual subsystem level improvements, will reduce the overall benchmark possession time by 40%.	The WP shall calculate the expected gain in possession time by applying the developed planning and scheduling tool. The elements used in this calculation (measured results, estimations, assumptions and extrapolations) shall be identified and quantified. The main elements that lead to the expected progress will be mentioned. Remark: This should be exercised for inspection as well as for maintenance activities.

Table J; Reference information for KPI_5 (Source: D1.2).

As presented during the first demonstration of the tool on the 18th of June, the estimated gain on possession time obtained using the planning and scheduling tool developed within WP5 varies from 6% to 15%. As different parameters can be optimized by the tool, this range illustrates the variability of gains on the possession time depending on which criterion is considered most important. Other criteria include for instance the distance travelled by machines, the gap between scheduled dates and target dates for operations, or the impact on commercial traffic.

It corresponds to the difference in possession time between a first planning generated with basic planning rules and an optimized planning generated with the help of optimization techniques (simulated annealing). Formally, this gain on possession time is computed using the following relationship:

KPI_5 = (1 - possession time after optimization / possession time before optimization) x 100%

These numerical results were obtained using a data set inspired from maintenance data of SNCF. It consists of a network of approximately 6.700 km, composed of 1.274 tracks and 704 points (arcs / edges of the underlying graph), where 200 maintenance operations are to be planned (measurement, tamping and grinding) and performed with the help of 6 maintenance trains.

2.3. Calculation of the overall effect.

Automain focuses on the whole set of the innovations. Therefore it is necessary to calculate the combined effect of all the innovations. The base for that calculation is the decrease of the possession time as predicted by the work packages. A summary of the decreases in possession time due to each work package is given below:

Work package 2 reports (see KPI_1):

- "The mean time used for tamping during a possession was **42%** leaving scope within the remaining 58% of the possession for improvement"
- "…where for tamping **6%** is the allowed time for transport and communications / confirmation"
- From the datasheet of WP2: KPI_1 = (1 – possession time required for maintenance using innovation / actual required possession time for maintenance) x100% = (1 – 0.71/1) x 100% = 29%

Work package 3 reports (see KPI_2):

- "A reduction in possession time **66%** can be achieved if (a) visual inspection is undertaken using overhead cameras, (b) geometry is assessed using train-borne measurement, (c) profiles of S&C are assessed using train-borne measurement, and (d) S&C uses smart washers and/or mechanically secured bolts."
- "A reduction in possession time **63%** can be achieved if (a) visual inspection is undertaken using overhead cameras, (b) geometry is assessed using hand-held measurement, (c) profiles of S&C are assessed using hand-held measurement, and (d) S&C uses smart washers and/or mechanically secured bolts."

Work package 4 reports (see KPI_3):

- "...40% improvement in the tamping activities gives about **35%** reduction in the track possession (See conclusion of D 4.2)"
- "The use of improved conventional grinding with 64 stones (considering reduced time for slag collection and reduced number of grinding passages) shows that reduction in track possession time in the order of **50%** is achievable (see Table 8 of D4.2)"

Work package 5 reports (see KPI_5):

- ….the estimated gain on possession time obtained using the planning and scheduling tool developed within WP5 varies from 6% to 15%.

Before the overall decrease of possession time is calculated we need to combine the effect of tamping and grinding on the objectives 1 and 3.

			objective 1 adopting best practices, lean approach			objective 3 adoption of innovative techniques for large scale maintenance		
		starting point	**reduction innovation WP2**	**result innovation WP2**	**total reduction innovation WP2**	**reduction innovation WP4**	**result innovation WP2 + WP4**	**total reduction innovation WP4**
	Action	hours (fictional)	[%]	hours (fictional)	[%]	[%]	hours (fictional)	[%]
tamping	time for tamping	42	0%	42		35%	27,3	
	transport / communications / confirmation	6	0%	6		0%	6	
	other --> possible reduction	52	100%	0			0	
	total possession time	**100**		**48**	**52%**		**33,3**	**31%**
grinding	time for grinding	71		71		50%	35,5	
	other --> possible reduction	29	100%	0			0	
	total possession time	**100**		**71**	**29%**		**35,5**	**50%**

combined reduction innovation								
tamping	grinding							
3	2				43%			38%
4	1				47%			35%

Table K; Effect of innovations on large scale maintenance (key tasks)

<u>Explanation of the calculations:</u>
Based on fictional absolute hours for tamping (100 hours) and grinding (100 hour), using the distribution of WP2 in column "starting point WP2" and the effect of the innovation of WP2, the remaining hours for WP2 are shown in column "result innovation WP2".
The innovations of WP4 reduce the (net) possession time for tamping with 35% and for grinding with 50% (column "reduction innovation WP4). The innovative techniques of WP4 only affect the time for tamping and not for transport / communication / confirmation. The remaining hours after the application of the innovations of WP2 and WP4 are shown in column "result innovation WP2 + WP4". This means that the total reduction is less than the percentage mentioned in WP4. This results in a total reduction due to WP4 in column "total reduction innovation WP4".

Based on the decrease of the possession time, as predicted by the work packages, and the distribution of possession times over the maintenance categories in the Netherlands we calculate the overall result of the innovations of Automain. The calculation of the overall effect of the innovations on the possession time is presented in Table L and Table M

Table L shows the reduction in possession time using the minimum predicted values:

- Objective 1, D2.1, D2.2: 43% (tamping to grinding ratio 3:2) [6]
- Objective 2, D3.1, D3.2: 63% (hand held measurement)
- Objective 3, D4.2: 38% (tamping to grinding ratio 3:2)
- Objective 5, D5.1, D5.2: 6%

[6] Tamping to grinding ratio 3:2 leads to lower reduction of possession time then ratio 4:1

	Annual possession time (fictional)		Objective 1 Adopting best practices	Objective 2 Novel track inspection	Objective 3 Innovation in large scale maintenance	Objective 5 Better planning & scheduling
Reduction (according to DoW)			*50% for key maintenance tasks.*	*75% for inspection*	*25% for large scale maintenance*	*resulting in 40% overall effect*
Relevant deliverables			*D2.1 D2.2*	*D3.1 D3.2*	*D4.2*	*D5.1 D5.2*
Reduction achieved by Workpackages			*43%*	*63%*	*38%*	*6%*
Maintenance task	actual hours	[%]	[%]	[%]	[%]	[%]
maintenance (key tasks)	483,2 hrs	17,9%	10,3%	10,3%	10,3%	9,6%
maintenance	1249,5 hrs	46,4%	46,4%	46,4%	46,4%	43,6%
large scale maintenance (key tasks)	322,1 hrs	12,0%	6,8%	6,8%	4,2%	4,0%
large scale maintenance	138,8 hrs	5,2%	5,2%	5,2%	3,2%	3,0%
inspection	500,0 hrs	18,6%	18,6%	6,9%	6,9%	6,5%
Total		100%	87%	76%	71%	**67%**
Effective overall reduction		-	**13%**	**12%**	**5%**	**4%**

Table L; Resulting reduction in possession time based on minimum predicted values.

Table M shows the reduction in possession time using the maximum predicted values:

- Objective 1, D2.1, D2.2: 47% (tamping to grinding ratio 4:1)
- Objective 2, D3.1, D3.2: 66% (train-borne measurement)
- Objective 3, D4.2: 35% (tamping to grinding ratio 4:1)
- Objective 5, D5.1, D5.2: 15%

	Annual possession time (fictional)		Objective 1 Adopting best practices	Objective 2 Novel track inspection	Objective 3 Innovation in large scale maintenance	Objective 5 Better planning & scheduling
Reduction (according to DoW)			*50% for key maintenance tasks.*	*75% for inspection*	*25% for large scale maintenance*	*resulting in 40% overall effect*
Relevant deliverables			*D2.1 D2.2*	*D3.1 D3.2*	*D4.2*	*D5.1 D5.2*
Reduction achieved by Workpackages			*47%*	*66%*	*35%*	*15%*
Maintenance task	actual hours	[%]	[%]	[%]	[%]	[%]
maintenance (key tasks)	483,2 hrs	17,9%	9,4%	9,4%	9,4%	8,0%
maintenance	1249,5 hrs	46,4%	46,4%	46,4%	46,4%	39,4%
large scale maintenance (key tasks)	322,1 hrs	12,0%	6,3%	6,3%	4,1%	3,5%
large scale maintenance	138,8 hrs	5,2%	5,2%	5,2%	3,4%	2,9%
inspection	500,0 hrs	18,6%	18,6%	6,3%	6,3%	5,4%
Total		100%	86%	74%	70%	**59%**
Effective overall reduction		-	**14%**	**12%**	**4%**	**10%**

Table M; Resulting reduction in possession time based on maximum predicted values.

2.4. Conclusions, remarks, some considerations regarding the overall results.

KPI	Objective	Maintenance task influenced by objective	Effective objective[7]	Result	Effective result[8]
1	50%	maintenance (key task), large scale maintenance (key task)	15%	43% - 47%	13% - 14%
2	75%	Inspection	14%	63% - 66%	12%
3	25%	large scale maintenance (key task), large scale maintenance	3%	38% - 41%	4% - 5%
4	50%	Future effect	-	unknown	unknown
5	Leading to 40% overall	all maintenance tasks	8%	6% - 15%	4% - 10%
Total result	40%		40%		**33% - 41%**

Table N; Overview of resulting reduction of possession times in terms of KPIs.

The decrease of possession time is depending on:

1. Each AUTOMAIN objective affects only a small part of the complete set of track possessions. The overall effect of each objective is thus much less than the initial target. E.g. the objective of 25% reduction by optimizing large scale maintenance (objective 3) leads to an overall effect of approximately 3%.
2. The exact overall effect of each objective can only be calculated on a national level. It depends strongly on the distribution of the several possession categories (= maintenance category). As these categories are not well defined, actual numbers are not available. In this report estimation (the Netherlands) has been used in order to get an impression of the results.
3. The AUTOMAIN goal to reduce the necessary possession time is true on a high level approach. In some situations the AUTOMAIN results will not lead to less possession times but will provide new opportunities to improve maintenance and e.g. introduce more inspections and preventative maintenance. In other words: AUTOMAIN results will lead to more work done without enlarging the capacity claim.
4. The overall reduction of the possession time can vary for each country and is strongly affected by:
   - The availability of the innovative tamping and grinding machines
   - The availability of freight trains that are able to do in service inspections
   - The amount of innovations that is being used simultaneously
   - Differences in (safety) regulations, working methods en planning practices, the distribution of possession types is certainly not valid for all countries and all situations. Therefore local practices will affect the overall effect of each objective.

[7] Refer to Table C for the calculation of the necessary effective percentage
[8] Refer to Table L and Table M for the calculation of the resulting effective percentage

- Level of maturity. Asset managers with high level of maturity will not reach the 40 % reduction of possession time.
- The realization of the assumptions made by the work packages.

3. Innovations.

3.1. Introduction and overview.

The innovations AUTOMAIN has been aiming to achieve will individually either speed-up and/or help optimise existing maintenance processes. However, if brought together, as shown in Figure 5, at the system level, the innovations will substantially reduce the current maintenance and possession times[9].

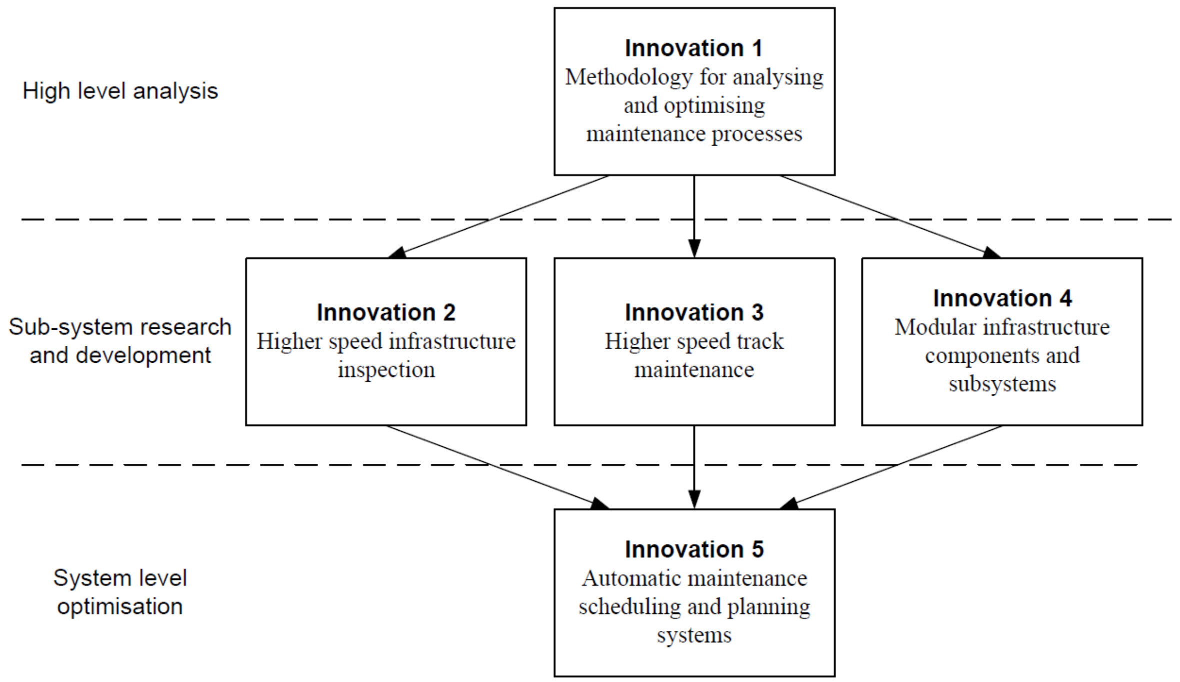

Figure 5; The individual AUTOMAIN innovations and their interdependencies (source: DoW).

In order to verify the innovations in the project, the consortium proposed in the DoW to use the Technology Readiness Levels (TRL) methodology (for definitions see *List of abbreviations and acronyms.* on page 5). This approach is used by NASA, the European Space Agency and many government parties around the world to assess the maturity of evolving technologies.

In the following chapter for each innovation the achievements will be described separately. This description starts with an explanation of the results, followed by a table showing the original objective. After that the results are matched against the evaluation criteria.

[9] Quoted from DoW.

3.2. *Innovation 1: A new methodology for analysing and optimising maintenance processes by applying best practice from other industries.*

The information to evaluate innovation 1 has been derived from WP2 and WP4.

3.2.1. Results.

The application of lean analysis in rail maintenance should be considered as the main innovation applied in WP2. Although this technique is in use in other industrial branches already for some time, it is not a commonly applied approach in railway maintenance. Referring to the existence and application of lean in other branches and the work done in WP2 and WP4 it can clearly be stated that this methodology has reached TRL-9 due to the work done in AUTOMAIN.

Tamping

The application of a lean approach itself does not create any improvements. However, it clearly creates insights in potential improvements and applicable innovations. By applying lean in tamping operations the analysis identified the following innovations that could contribute to a 21% reduction in possession times for tamping:

Automatic machines reducing operator variability and optimising machine performance. The technology for automatic tamping machines (as for driverless trains) is well understood, but the variability of infrastructure design and sleeper spacing requires highly reliable machine vision. It is feasible that there is sufficient knowledge to build a system prototype for demonstration in a railway environment, establishing this innovation at TRL 7.

Tamping machines capable of tamping 1, 2, 3 or 4 sleepers and switches to ensure that the machine is always capable of high performance on any work site. These individual attributes are available but as far as is known, they are not combined into a single all-purpose machine. As above, this innovation should be regarded as TRL 7.

In circumstances where track quality could be recovered by spot tamping a 100% reduction in possession time could be achieved through the development of:

Small high speed tamping machines for short degraded track sections followed by high speed running to the next site, permitting tamping between commercial services. The use of track force reduction technologies such as under sleeper pads and improved bogie designs may reduce the need for tamping long track sections. The technology to build such a machine is available; it only requires a strong business case. TRL 7 to 8.

Grinding

The application of lean analysis in grinding operations identified the following innovations that could contribute to a 52% reduction in possession times for grinding:

Utilisation of a temporary switch allowing stabling for the grinding machine close to the possession. Temporary switches are currently used in a number of countries including London Underground. The

Martinus Rail (Australia) website (martinusrail.com.au) has a detailed description with photographs of their temporary switch for this exact purpose. Therefore this is at TRL 9.

Grinding machines equipped with rail profile measurement and ACFM (or equivalent) crack detection capability eliminating the need for manual checks. Provided that the rail is not contaminated with grinding debris, this innovation may be achieved by attaching an inspection vehicle to the grinder. TRL 8

Rail head re-profiling machines (grinding, milling or planing) capable of 80kph operation. 80 kph is possible with high speed grinding machines (e.g. DB) although it requires three passes (or three machines in convoy) to remove 0.1mm of rail head. This innovation is therefore at TRL 9, only requiring a sufficiently strong business case before introduction

The combination of the above innovations could allow full utilisation of the available possession time once the necessary shift safety procedure has been completed. Without a machine speed increase, this would provide a 52% reduction in possession time.

The above reduction combined with 80kph operation could yield a 92% reduction or 100% where the grinding train was capable of operating within the existing timetable.

3.2.2. Evaluation.

i.	Primary KPI: KPI_1 = (1 – possession time required for maintenance using innovation / actual required possession time for maintenance) x100%
ii.	Capability requirements: CR05, CR07, CR10, CR11, CR12, CR13, CR14, CR15.
iii.	Primary objective: To adopt best practice from other industries in inspection and maintenance optimisation (e.g. highways, aerospace). The project will demonstrate how the benchmark possession time for key maintenance tasks can be reduced by up to 50% (Objective 1).
iv.	Current Technology Readiness Level: TRL 4 - component validation in a laboratory environment.
v.	Final Technology Readiness Level: TRL 8 - actual system completed and qualified through test and demonstration.
vi.	Critical success criterion: Possession time for key maintenance tasks (e.g. tamping) to be reduced by 50%. This should be assessed through detailed analysis and DS1 and DS2.

Table O; Overview of the evaluation criteria of innovation 1 (Source: D1.2).

- **KPI_1**: 43 – 47% (ref. to 2.2.1)
- **Capability requirements**: not assessed separately.
- **Primary objective:** The lean approach has been adopted from other industries and elaborately applied in rail-maintenance situations. The showcases show a clear potential to reduce the possession times for key maintenance tasks with over 50%.
- **Final TRL:** As the approach has been applied in situations outside AUTOMAIN and WP2 afterwards, the applicability can be regarded as proven: TRL 9.
- **Critical success criterion**: It has been shown that the approach leads to opportunities that could reduce the possession time with 50%. This has not been assessed in the demonstrators.

3.3. Innovation 2: Higher Performance infrastructure inspection methods.

The information to evaluate innovation 2 has been derived from WP3 and WP4.

3.3.1. Results.

Overhead camera for visual inspection.

An overhead, catenary mounted camera has been developed by Damill in Sweden, System prototype demonstrated in a railway environment in Boden, Sweden.

This category involves the visual inspections carried out by staff through S&C, typically viewed from vertically above the infrastructure, or by kneeling down to view the infrastructure from other angles. On average, it is estimated to take 15 minutes to visually inspect a full set of S&C, and the periodicity is estimated to be on average 2 weeks.

Technology readiness level estimated at TRL 7.

Hand-held measurement systems for geometry measurement, profile, shape and position of S&C components.

As documented in Deliverable D3.2, the University of Birmingham has developed a laser based trolley for S&C inspection as part of the AUTOMAIN project. This trolley is primarily intended to be used by the S&C weld and grind repair teams as quality control equipment assisting them throughout the repair process.

It is difficult to accurately assess the reduction in possession time that results from the improved ability to inspect and assess the quality of repair work as a result of the use of the trolley as this depends on a number of factors including:

- the current condition of S&C;
- the rate of degradation, particularly of badly repaired S&C components;
- standards (e.g. intervention limit, rate of inspection);
- variability in the failure rate for repairs.

However, through discussions with Network Rail it has been identified that it can take up to 15 minutes to carry out a full switch inspection. The hand-held laser based trolley automates much of this process and therefore an inspection time of 5 minutes is achievable in a railway environment, thus reducing the inspection time by 66%. Initial trials within in WP6.2 demonstrated that the inspection time using the hand-held laser based trolley could be consistently achieved in less than 5 minutes. This reduction is inspection time is directly related to the possession time required for switch inspection.

The hand-held switch measurement system, developed by the UoB, was demonstrated in a railway environment at Long Marston Test Track, Stratford-upon-Avon, UK.

Technology readiness level of the hand-held system is estimated at TRL 7

Train-borne measurement systems for geometry measurement, profile, shape and position of S&C components.

The project enhanced the existing Switch Inspection and Measurement (SIM) system available by Strukton through the development of further data analysis software and vehicle position devices. These innovations allowed the SIM system to be used as part of the DB switch inspection regime.

As part of the WP6.1 trials in Germany 963 switches were inspected, taking a total time of 46 hours and 21 minutes. This was achieved without taking any possessions. Table P shows the details of the four inspection trials that took place.

Station	Number of Switches	Time	Night/Day
Nürnberg	266	14:59	N+D
Ingolstadt	210	14:38	N+D
München	392	06:56	N+N
Rosenheim	95	09:48	N+D
	963	**46:21**	

Table P; Overview of the effect of the application of train-borne switch inspection.

Geometry measurements are currently carried out manually in general. On average it takes 15 minutes to measure a typical set of S&C, and the periodicity is every 6 months. The other geometry inspection tasks include those where millimetre accuracy is required, and a tool such as a manual inspection gauge is usually used to measure parts of the S&C, usually relating to the profile, shape or position of the inspected part. On average it takes 30 minutes to undertake the measurements, and the periodicity is typically 4 months.

The train-borne system has an estimated TRL of 8.

Smart washers for monitoring tightness and security of S&C components

The development of smart washers which measure torque and remotely send the data to a server, or installation of mechanically secured bolts which cannot come undone. The smart washer technology has been demonstrated by the University of Birmingham and others, and there are a number of commercially available products that secure bolts mechanically.

The inspection requirements involve checking the tightness of S&C components, and in many cases verify that the applied torque on securing bolts is within acceptable limits. These checks are done on average every 3 months, and they typically take 15 minutes to complete.

Technology readiness level is estimated as TRL 4-9.

3.3.2. Evaluation.

i.	**Primary KPI:** KPI_2 = (1 – possession time required for inspection using the novel approach/ actual required possession time for inspection) x100%
ii.	**Capability requirements:** CR01, CR02, CR03, CR04, CR09, CR21, CR22.
iii.	**Primary objective:** To develop novel track inspection approaches for freight and mixed traffic routes. The project will demonstrate how the benchmark for possession time for track inspection can be reduced by up to 75% (Objective 2).
iv.	**Current Technology Readiness Level:** TRL 4 - component validation in a laboratory environment.
v.	**Final Technology Readiness Level:** TRL 7 – system prototype demonstration in a railway environment.
vi.	**Critical success criterion:** Possession time for track inspection (e.g. switch and crossing inspection) to be reduced by 75%. This should be assessed through DS1 and DS2.

Table Q; Overview of the evaluation criteria of innovation 2 (Source: D1.2).

- **KPI_2**: 63-66% (refer to §2.2.2)
- **Capability requirements**: not assessed separately.
- **Primary objective:** Novel inspection approaches have been developed and tested: overhead camera, train-borne switch inspection, train-borne geometry measurements, and hand-held switch inspection.

- **Final TRL:** the developed technologies are in different TRL scores. Most of them between 7 and 9.
- **Critical success criterion:** Several inspection techniques have been applied in the demonstrators of WP6.

3.4. Innovation 3: Higher Performance track maintenance methods.

The information to evaluate innovation 3 has been derived from WP3 and WP4.

3.4.1. Results.

High Speed Grinding

High Speed Grinding (HSG) can decrease the position time of track due to maintenance action grinding. This is a new concept with a high operates at speeds of 60 - 80 km/h, the grinding train can fit in a normal train slot. The grinding stones are self-propelled by the train speed. Simulations show a large gain with smaller positions time by using the HSG. This concept is in use in Germany but need to be tested on other countries.

As the technology is actually being used in a country, a TRL 8 is estimated.

Fast slag collection

A fast slag collector is manufactured by a Canadian company Protec MIV. It can collect slag at more than 10 km/h and also extinguish line side fires. It collects slag with a speed up to 20 km/h. The speed of the collector has to be higher than the grinding speed so that it manages to collect the slag in between the grinding passes. Simulations show a gain with fast slag collection due positions time.

Estimated TRL 7.

Combination of grinding machine

It will be possible to couple two normal HSG trains together to create an HSG Twin Train and increase the capacity. Combining two HSG machines can decrease the track possession time for grinding. The efficiency in terms of reduction of track possession time as well as economic implications have been simulated in this project, although the quality output on rail condition is not confirmed in this report.

Knowing that this is existing technology innovatively applied, a TRL 7 is estimated.

Single failure tamping

Detailed investigation shows clearly, that the use of improved single tamping machine, which are able to restore the track geometry over a length of more than 15 m will reduce the need for tamping the whole section. The automatic identification of the needed tamping parameters from the adjacent track that has good track geometry will increase the efficiency and reduces the possession time. Such a machine has to be developed in the future for the requirements of IMs.

Effective root cause analysis method

Removing the root causes for single track geometry defects will strongly reduce the needs for the currently inefficient maintenance of weak spots. If it is possible to avoid or reduce the number of weak spots the tamping can be carried out much more efficiently by high performance machines like four sleeper tamping machines which are able to tamp 2000m/h.

Automated control of tamping machine

The automated control of the tamping machine parameters like pressure or time of intrusion will lead to a more homogenous ballast bed. The manual control and adjustment of tamping parameters requires additional concentration of the operator and a high quality can't be achieved for the whole night.

Combined maintenance activities

The planning and scheduling of combined maintenance activities like tamping and grinding increases the planning efforts but noticeable reduces the possession time. Especially in case of preventive maintenance longer sections of the track will be maintained and several shifts are linked. In this case the combination of fast grinding and slow tamping machines are possible. Perhaps the use of two tamping machines followed one shift later by the grinding machine will reduce the possession time and increase the achieved quality of the maintenance.

Estimated TRL: 6, prototype demonstrations have been executed.

Robust database and data system. (Blue sky)

Many concerns were raised during the lean analysis of grinding, tamping and modular S&C, including the following:

- Inaccurate data on track condition.
- Automate the production of post-maintenance reports and uploading of these to the central database.
- Improve on-board measurement equipment, so that manual on-track measurements are no longer required.
- Better use of track geometry and condition data.
- No history of earlier performed maintenance.

A blue sky, "single central system" solution is presented in Figure 6. A robust on-line database and data system can provide the necessary data and the decision support to all parties involved in the railway maintenance process. The core modules include a number of central databases with analysis and reporting tools. These databases store and provide data such as maintenance history, e.g. what kind of maintenance has been performed, where and when. Another database stores pre-measurement data combined with inspection data i.e. to support trending of the degradation from the designed position of the track. This is necessary as a control measure, because if the track moves from its designed position with stress-free rail temperature, the inbuilt track forces will increase and the risk of sun buckling and rail cracks will increase. All maintenance vehicles will be tagged with RFID (Radio Frequency Identifications) containing information on the type and capacity of the vehicle. They will also have GPS-equipment that can provide information on their position. Before the maintenance activity can start, the maintenance operator must push a button and insert the type of maintenance to be performed (preventive or corrective), and if the vehicle is on a station, insert the track number. As soon as this information has been inserted, a panel in the vehicle will receive information e.g. deviations from pre-measurement data, measured quality, and earlier conducted maintenance on this spot. The maintenance activity can then start; when finished, the operator pushes the "off" button, and the system will send maintenance data back to the central system, including the quality of the performed maintenance. The central system will then calculate the expected degradation and plan the next maintenance.

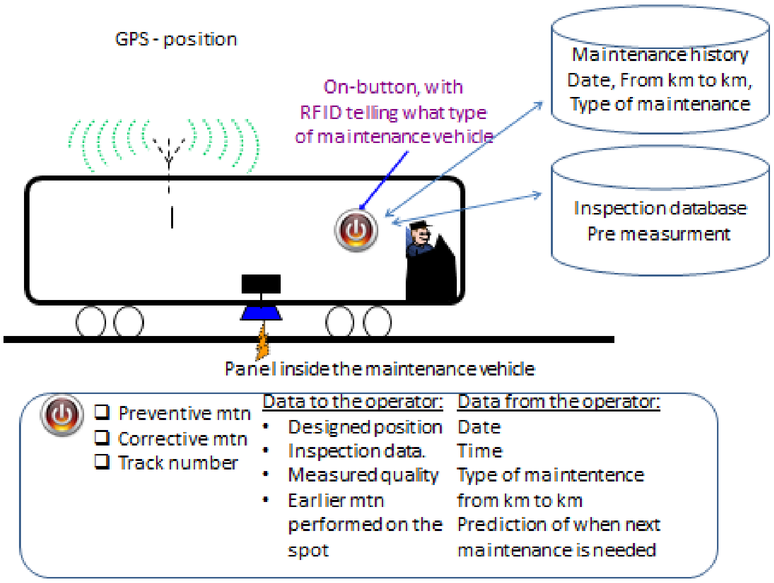

Figure 6; Single central system for maintenance decision support.

3.4.2. **Evaluation.**

i.	**Primary KPI:** KPI_3 = (1- total possession time required for maintenance using innovative techniques/ actual required possession time for maintenance) x100
ii.	**Capability requirements:** CR06, CR07, CR08, CR09, CR10, CR11, CR12, CR13, CR14, CR15, CR20, CR21, CR22, CR23.
iii.	**Primary objective:** To research and assess innovations that have the potential to improve the effectiveness and efficiency of large scale maintenance processes (e.g. grinding and tamping). The project will undertake simulations to show how these technologies can reduce the benchmark possession time by up to 25%.
iv.	**Current Technology Readiness Level:** TRL 3 – analytical and experimental critical function and/or characteristic proof-of-concept.
v.	**Final Technology Readiness Level:** TRL 6 – system/subsystem model or prototype demonstration in a railway environment.
vi.	**Critical success criterion:** Possession time for track maintenance (e.g. grinding) to be reduced by 25%. This should be assessed through detailed analysis.

Table R; Overview of the evaluation criteria of innovation 3 (Source: D1.2).

- **KPI$_3$**: 38 – 41% (refer to 2.2.3)
- **Capability requirements**: not assessed separately.
- **Primary objective**: The objective has been reached.
- **Final TRL**: 6-8
- **Critical success criterion**: Several models have been developed and calculated to assess the potential reduction in possession time.

3.5. Innovation 4: Modular infrastructure components and subsystems which lend themselves to automated removal and fitment.

The information to evaluate innovation 4 has been derived from WP4.

3.5.1. **Results.**

General view on modularization.

Modularization is a term both in construction and in maintenance of an asset. A modularized asset is easier to install and maintain than an asset built without modules. The term can be used for showing the possibility to replace larger unit instead of components. The larger unit can be repaired at the workshop where the condition for repair is better than in the field. The term is also used to separate expensive components (which have a low failure rate) from inexpensive components that have a higher failure rate.

For S&Cs modularization has been used in building point machines with several repairable units that in field is replaced and repaired in work shop. Modularization of the crossing has also been discussed where the crossing can be replaced with or without the sleepers so the surface welding can be done in workshop instead of the field. When replacing sleepers a restoration of the track geometry is also possible.

Switches & crossings are built up with different components and subcomponents. The basic components are the different steel parts (switch blades, stockrails, crossings, checkrail, baseplates, slide chairs etc.), sleepers and point machines. S&Cs also includes sub components such as detection devices, heating system etc. Instead of handle S&Cs in separate components in aspects of installation, inspection and maintenance they shall be seen as modules. These modules are defined as follows:

- Distinct parts (mouldes)
- A clear specification of WHAT is to be done in terms of repair and maintenance (standard work).
- A clear specification of HOW repair and maintenance is to be done (standard work).

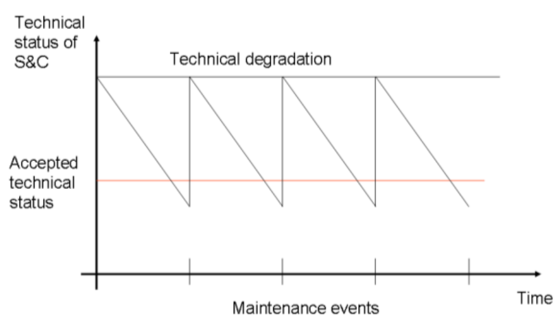

Figure 7; Theoretical technical status when everything degraded is renewed by maintenance.

A study of the maintenance process at

Trafikverket "Maintenance and replacement of Switches & crossings within Trafikverket" (6) found that there are no fixed rules or standards on how to manage or carry out maintenance. Normally, the S&Cs are checked regularly; the frequency is based upon the type of track, traffic load and speed. When the result of the inspection is outside specifications, someone must decide what maintenance should be done. If every component and sub-component which has been degraded is renewed during the maintenance activity, the curve of the technical status would look like Figure 7.

Figure 7 shows regular degradation; the timing of the next maintenance activity is easy to predict, since it will come at a regular interval.

This is not the case in reality, however. Normally, inspection personnel do the measuring and compare the result to the existing standard. In this comparison, a certain wear can usually be noticed. Often this wear is still within stated tolerance levels; therefore, it is not necessary to do anything. Nevertheless, it is a degradation which affects other components in the global S&C system.

In the switch part, the most replaced steel part is the curved switchblade. The crossing part is a little more complex since there is a direct relation between the checkrail and the crossing when it comes to safety and both components show wear. The need of a good transfer or wheel requires the crossing to have good geometry and a good profile. The root cause of problems in crossings is high vertical and lateral forces in combination with bad contact geometry. It is very important that maintenance has good results.

The most common maintenance activities in the crossing area are adjusting the checkrail with shims for better safety and welding the crossing for optimal geometry. Aspects like correct over-all geometry or good track quality when it comes to levelness and stiffness not concerns in this process. Due to the gap between what is really degraded and what is renewed during a maintenance event, the curve of the technical status will be as shown in Figure 8.

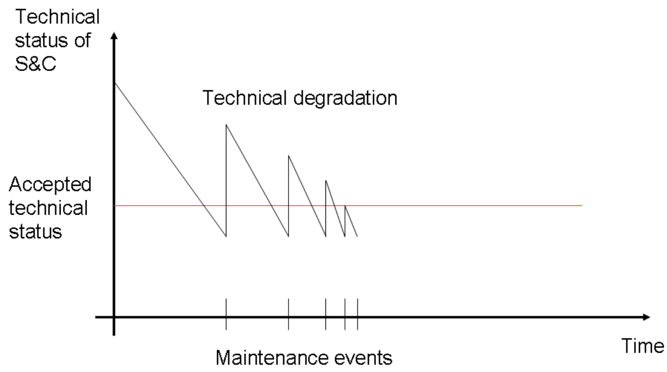

Figure 8; The degradation of the technical status when only some parts of the S&C are renewed during maintenance event.

When only some parts of the S&C are renewed, a negative degradation trend begins, because after maintenance, the S&C is not at the same high technical level as when it was new. A big part of the S&C system has not been renewed at all and in some parts not to the same level as when new. The output from the renewal activity is at a lower technical level for each maintenance event; at the same time, the events become more frequent.

"Guidelines for modularisation of S&C" (one of the documents produced by AUTOMAIN, apart from the deliverables) recommended the establishment of function structures by reducing the number of sub-functions and combining several sub-functions into a single module. This is supported by the service contractors; in general, they prefer large modules.

By defining modules, create standard work for *what* to be done and *how* there will be a number of improvements:

- Knowledge of what to do
- Knowledge of how to do it
- Knowledge of how long it will take
- Knowledge of the technical result
- Higher technical result
- Less total time in track for installation, inspection, decision/planning of actions and maintenance

A replacement strategy means that repair work is done in a workshop, not on the track. There are many advantages to this:

- With a standard crossing replacement, the necessary time for replacement can be less than four hours.
- A quick replacement process means fewer people on the track.
- A repair done off the track have better quality due to better conditions.

Modular switch design.

A modular design that has been incorporated is the movable crossing blade that is possible to replace without replacing the whole crossing, which in essential is the wing rail surrounding the movable crossing blade.

Figure 9 shows a complete crossing with movable crossing blade. The part that is normally worn or damaged the most is the movable blade, in red colour.

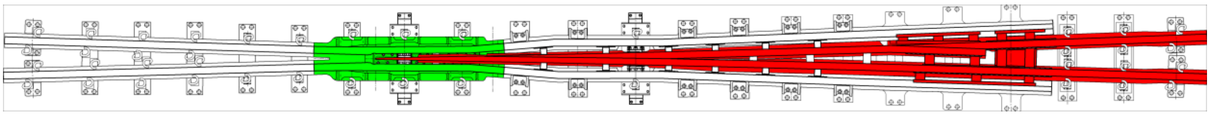

Figure 9; Crossing with movable blade.

In the rear of the movable blade, the fixation is built up with a ground plate in the crossing, see green area in Figure 10 , in which the wing rails are attached. The wing rails are machined in order to easily fit a loose movable blade. The modification can be done in a smooth and efficient way.

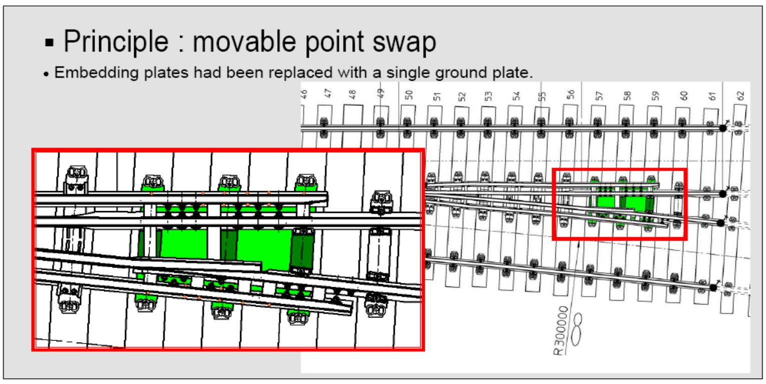

Figure 10; Detail of the fixation of the movable blade.

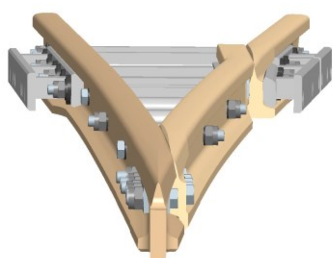

Figure 11; The movable blade.

Another *modular replacement* which also has been studied is using *panel replacement* instead of replacing single components. The crossing panel in S&Cs with fixed nose crossings is a very good example in which normally the impacts from the wheel are not only cause wear on the crossing itself. It also causes wear at the check rails and goes also down to the rail pads, sleepers and ballast. In contrast to multiple single component replacements, panel replacement can restore the technical level of the whole system.

Figure 12; Transportation of a crossing panel in Falun, Sweden.

3.5.2. Evaluation.

i.	**Primary KPI:** KPI_4 = (1- possession time required after using modular elements/ actual required possession time) x100%
ii.	**Capability requirements:** CR05, CR10, CR11, CR12, CR13, CR14, CR15, CR20, CR23, CR30.
iii.	**Primary objective:** To develop further key technologies that will drive the development of modular infrastructure design. It will be demonstrated during the project that these technologies can reduce the benchmark possession time for installation, maintenance and inspection during the life of the asset by at least 50%.
iv.	**Current Technology Readiness Level:** TRL 2 – Technology concept and/or application formulated.
v.	**Final Technology Readiness Level:** TRL 6 – system/subsystem model or prototype demonstration in a railway environment.
vi.	**Critical success criterion:** Possession time for installation, maintenance and inspection (e.g. point machines) to be reduced by 50%. This should be assessed through detailed analysis and DS2.

Table 5; Overview of the evaluation criteria of innovation 4 (Source: D1.2).

- **KPI_4**: unknown (refer to 2.2.4)
- **Capability requirements**: not assessed separately.
- **Primary objective**: Technologies have been developed. However it has not been calculated in what way these developments will contribute to a reduced possession time.
- **Final TRL**: Not provided
- **Critical success criterion**: Unknown

3.6. Innovation 5: The improvement of automatic maintenance scheduling and planning systems, which focus on scheduling maintenance around the timetable, so as to reduce disruption to scheduled traffic and to increase useful capacity.

3.6.1. Results from WP5.

Inserting maintenance activities between train paths, and minimizing the impact of maintenance on commercial traffic is the role of the TWIP (Time Window Insertion Problem) module. The latest results obtained with this module show that significant gains can be achieved by the optimization algorithms compared with more basic approaches. By carefully choosing the best time to start the operation, and by slightly modifying a few train schedules, it enables to reduce the number of cancelled trains.

Besides, the long-term planning module itself enables to reduce the number of possessions by combining maintenance activities, hence to increase useful capacity.

In terms of TRL, we estimate that WP5 developed technology from TRL 2 to TRL 4 (Component and/or breadboard validation in laboratory environment). Indeed, despite inputs from Infrastructure Managers were requested in the early stages of the project, one major difficulty faced by WP5 was the lack of real data in an appropriate timing. Our algorithms could only prove their efficiency over a few examples. We could not measure the gains on a broad variety of situations coming from different European countries. For this reason, we believe that the expectations of gain should be considered as an example of achievable result rather than a guarantee that such reduction of possession time will be obtained in any particular situation.

3.6.2. Evaluation.

i.	**Primary KPI:** KPI_5 = (1 – possession time needed when using innovative scheduling tool/ actual needed possession time) x100%
ii.	**Capability requirements:** CR07, CR10, CR11, CR12, CR22, CR31.
iii.	**Primary objective:** To develop a new maintenance planning and scheduling tool that is able to optimise the programme of required maintenance activities, taking account of the benefits brought about by other improvements in the AUTOMAIN project. The tool, together with the other individual subsystem level improvements will reduce the overall benchmark possession time by 40%.
iv.	**Current Technology Readiness Level:** TRL 2 – Technology concept and/or application formulated.
v.	**Final Technology Readiness Level:** TRL 7 – system prototype demonstration in a railway environment.
vi.	**Critical success criterion:** Overall possession time for maintenance tasks to be reduced by 40%.[10] This should be assessed through detailed analysis and DS1 and DS2.

Table T; Overview of the evaluation criteria of innovation 5 (Source: D1.2).

- **KPI_5**: 6% - 14%, to be considered as an example of achievable result (see text above).
- **Capability requirements**: not assessed separately.

[10] This text differs from the one in D1.2. The text in D1.2 did not cover the original objective 5.

- **Primary objective**: The framework of the planning tool is developed and proven. Demonstrations have been based on a more or less theoretical set of data, not on output from other WPs yet.
- **Final TRL**: TRL4. Due to technical problems the PW succeeded in having a working prototype using a theoretical dataset.
- **Critical success criterion**: Demonstration with an available dataset showed a reduction of 6 – 14%, where detailed analysis of the objective shows that 8% will lead to 40% overall (ref. to Table C).

3.7. Overview and conclusions.

The overview in Table U shows a summary of the results of the AUTOMAIN innovations.

Innovation	1	2	3	4	5
KPI	✓	✓	✓	?	✓
Comments:	43-47%	An improvement of 63-66% has been shown, where 75% was the objective.	38-41%		6-15%.
Primary objective	✓	✓	✓	?	✓
Final TRL	✓	✓	✓	?	✗
Comments:	TRL9, where the objective was TRL8.	Depending on the developed technique between 2 and 9.	TRL 6-8		TRL4 reached. TRL 7 turned out to be too ambitious in the scope of the program.
Critical success criterion	✓	✓	✓	?	✓
Comments:		Demonstrated in WP6.			

Table U; Overview of the evaluation criteria and the results per innovation.

4. Planning tool

4.1. Overview of results of WP5.

In D1.2 an overview of the relation between the planning and scheduling problems was given. We use this overview to evaluate the results of WP5 regarding the end-user requirements.

Requirement as formulated in D1.2	Evaluation of the WP5 result.
Data visualization: both TWIP and WSSP will generate a basic graphical representation of the generated schedules. On the contrary, the results of planning problems are list of tasks assigned to each day or week. Such lists can of course be visualized, but they contain no graphics.	The LTP modules generates Gantt diagrams representing planning solutions over a time horizon of a few months, whereas the TWIP module produces space-time diagram over 24 hour-periods.
Conflict detection, Track possession minimization: these requirements are basic and common to any track maintenance planning or scheduling problem, so they strongly concern all four posed problems.	Several types of conflicts are handled by the tool: resource usage, overlapping operations, train paths conflicting with each other, etc.
Planning assessment: Only LTPP and DynPP will be planning tools, i.e. they assess optimised maintenance plans.	The LTP module is a proper planning tool, generating planning solutions over a time horizon of a few months. It enables to dynamically insert new operations ("DynPP" feature)
Scheduling assessment: only TWIP and WSSP are scheduling problems, i.e. they assess optimised schedules.	The TWIP module is a proper scheduling tool generating detailed maintenance schedule, inserted into commercial grid.
Work load balancing: since load balancing refers to *long term* balancing, this requirement concerns only LTPP and DynPP, which have larger planning horizons. However, DynPP handles only the rescheduling of a bunch of interventions, the majority of them remaining unchanged, so that its rebalancing capacity is limited.	The LTP module balances the workload between machines by ensuring that all operations are performed on time, given their respective deadlines. Moreover, the distance travelled by machines between maintenance operations is minimized.
Critical resource use optimisation: similarly to load balancing, at short term scheduling there is no big potential for resource allocation optimisation. Critical resource optimisation concerns rather long term planning. Again, the fact that DynPP only deals with rescheduling of some interventions limits its optimisations potential.	The LTP module is responsible for find planning solutions including all operations to be performed, while minimizing the variable workload constituted by machine travels.
Rescheduling to decrease constraint violations: This is one of the main objectives of WSSP and DynPP (strictly speaking, DynPP deals with *re-planning* rather than *re-scheduling*). Also TWIP	The TWG module is responsible for finding the best way to split large operations into several shorter operations which are then inserted into 24 hour-windows by the TWIP module, thus

Requirement as formulated in D1.2	Evaluation of the WP5 result.
can be used for improving one day's schedule. On the contrary, LTPP is oriented to the creation of a long term plan rather than rescheduling.	handling the possibility of conflicts between maintenance and commercial train paths.
Over-maintenance avoidance: as stated in D1.2 section 4.1, the decision on what maintenance actions are necessarily falls out of the scope of WP5. Hence *all four posed problems need the list of maintenance operations to be planned/scheduled as* input *data*. However, LTPP may help to keep they right periodicity of periodic interventions, thus helping to avoid interventions take place too soon or too late. In this sense, LTPP is also related to over-maintenance avoidance.	The number of operations (and, hence, their frequency) is not a choice made by the tool. However, the tool minimizes the gap between the "target date" of operations and the actual dates they are planned, thus enabling to optimize the periodicity of operations. Consequently, target dates must be chosen with care in the input data as they have a great impact on reducing over-maintenance.
Operations combination: Only TWIP does not consider directly task combinations. This is because it takes time windows as input data and just tries to fit them into a feasible schedule. However, if the size of the time windows delivered to TWIP are calculated using WSSP, the task combination will be considered by WSSP. Besides WSSP, also LTPP and DynPP need a list of allowed task combinations as input, which will be considered for planning.	The optimization performed by the LTP module directly comes from the possibility of combining compatible operations. Moreover, even though it is not an explicit objective of it, the TWIP module is able to successively schedule combined operations, taking into account already scheduled operations.
Consider track possession and resources constraints: since TWIP and DynPP consider all scheduled trains (microscopic level), they take detailed account of track possession constraints. On the contrary, WSSP and LTPP assume that the time window length in known in advance (macroscopic level), so they do consider track possession constraints explicitly, but at a lower level of detail.	On the one hand, the TWIP module precisely takes into account track possession, as it handles microscopic constraints. On the other hand, the LTP module also takes into account track possession as it may not plan overlapping operations on the same days. It also takes into account resources constraint : sufficient time must be allowed between successive operations on the same machine to allow its travel.

Table V; Overview of the requirements and their evaluation relevant for WP5.

4.2. Conclusions, remarks and considerations.

The planning and scheduling tool developed by WP5 proved that the concept of combining operations enables to achieve significant reduction in possession time. This was its main objective. However, it went further in several aspects:

- It explicitly considered the use of maintenance machines, which are critical resources because of their cost and their rarity. The use of these resources was optimized by applying dedicated techniques to minimize the travel between operations.
- It considered the details of maintenance scheduling associated with each operation, to make sure that the suggested dates/machines could indeed be respected, given the local conditions.
- It integrates both long-term planning and more detailed scheduling into a single tool.

- It showed that optimizing additional criteria was possible, without dropping the possession time reduction objective: the distance travelled by machines, the gap between target dates and actual dates and the impact on commercial traffic are also minimized.

It should be noted here that, due to the volume and precision required from the input data expected by the tool, this latter could be tested only on a single data set. This means that the numerical results obtained might be different (but not necessarily less good) on other instances.

5. Demonstrations

The objective of the demonstration phase of the project is to verify the practicality and results of the innovation researched and developed in the project and to work towards increasing the Technology Readiness Levels of these innovations.

Two main demonstrations were undertaken:

WP6.1 – In-service track monitoring

WP6.2 – Modular self-inspection switch

5.1. WP6.1 – In-service Track Monitoring

Within WP6.1 in-service track monitoring has been demonstrated in the UK on the London to Brighton line, and in Germany and the Netherlands on the Rotterdam to Dillingen freight line.

The key objectives of WP6.1 were:

Objective 1 was 'to adopt best practice from other industries in inspection and maintenance optimisation (e.g. highways, aerospace), and demonstrate how the benchmark possession time for key maintenance tasks can be reduced by up to 50%'.

Objective 2 was 'to develop novel track inspection approaches for freight and mixed traffic routes, and demonstrate how the benchmark for possession time for track inspection can be reduced by up to 75%'.

Objective 5 was 'to develop a new maintenance planning and scheduling tool that is able to optimise the programme of required maintenance activities, taking account of the benefits brought about by other improvements in the AUTOMAIN project. The tool, together with the other individual subsystem level improvements will reduce the overall benchmark possession time by 40%'.

The results of these objectives have been previously been quantified in the innovations section of this report. However, additionally, WP6.1 aimed to address the following functional requirements. The table below shows the details of these requirements, and a summary of how WP6.1 has addressed these requirements:

Functional requirement ID	FR01
Capability Requirement ID	CR01
Functional requirement	To be able to collect performance and condition data using automated methods.
Source	WP3, WP4
Validation	The WP's have to show that their data collection process is fully automated.
Performance	No human interaction is needed in collecting data and disclosure of data to the user.
Constraints	Not relevant for manual measuring methods.
Verification	In WP6
Comments	By avoiding human interaction in the data collection process, the chance of introducing mistakes is diminished, the continuous availability of data is improved and the costs of data collection can be reduced.
WP result	This requirement has been met in both demonstration scenarios. Within DS1 it has been shown that track monitoring data can be collected using a 'fit and forget' data acquisition system. This has been demonstrated in the UK and will be later

	demonstrated in Germany. This significantly reduces the need of personnel to access the track to monitor track geometry, and find further information regarding specific positions where faults are located.

Table W; Description of functional requirement 1 and its results in DS1 (source D1.1).

Functional requirement ID	FR08
Capability Requirement ID	CR08
Functional requirement	To be able to use recorded loads applied to the track.
Source	WP3 (T3.2)
Validation	WP shall show the results of the measurements.
Performance	Accuracy of the measurement has to be defined in the WP.
Constraints	Track only.
Verification	WP6
Comments	Cumulative load is expected to be a main indicator for preventative maintenance and quality assessment. Several systems such as Gotcha, DafuR and others are already in use. Same load but different settlement in the track of the switch results in different lifetime and “health”.
WP result	Within DS1, algorithms have been developed to autonomously process the track data collected. These algorithms are able to identify faults, and then monitor these faults over time to observe their degradation as increase loads are applied to them . This approach allows maintenance personnel to observe and predict the degradation of track faults in specific locations. This allows maintenance to be more effectively planned.

Table X; Description of functional requirement 8 and its results in DS1 (source D.1.1).

5.2. WP6.2 – Modular Self-inspecting Switch

WP6.2 brings together a number of switch inspection innovations to form a modular solution. These solutions have been demonstrated at various locations throughout Europe.

Visual inspection – overhead camera

- Proposed new technology: overhead catenary mounted switch inspection camera.
- New possession time / reduction percentage: 0 min / 100%.

Technology readiness level estimated at TRL 7. System prototype demonstrated in a railway environment in Boden, Sweden.

Geometry measurement

- Proposed technology: hand-held switch measurement system (individual switches), or train-borne switch measurement system (groups of switches)
- New possession time / reduction percentage: 5 min / 66% (hand-held); 0 min / 100% (train-borne)
- Technology readiness level estimated at TRL 7 (hand-held). System/subsystem model or prototype demonstration in a railway environment at Long Marston Test Track, Stratford-upon-Avon, UK.
- Technology readiness level estimated at TRL 8 (train-borne). Train-borne system demonstrated at four locations (963 switches) in Germany.

Profile, shape and position of S&C components

- Proposed technology: hand-held switch measurement system (individual switches), or train-borne switch measurement system (groups of switches)
- New possession time / reduction percentage: 5 min / 83% (hand-held); 0 min / 100% (train-borne)
- Technology readiness level estimated at TRL 7 (hand-held). System/subsystem model or prototype demonstration in a railway environment at Long Marston Test Track, Stratford-upon-Avon, UK.
- Technology readiness level estimated at TRL 8 (train-borne). Train-borne system demonstrated at four locations (963 switches) in Germany.

The key objectives of WP6.1 were:
Objective 1 was 'to adopt best practice from other industries in inspection and maintenance optimisation (e.g. highways, aerospace), and demonstrate how the benchmark possession time for key maintenance tasks can be reduced by up to 50%'.
Objective 2 was 'to develop novel track inspection approaches for freight and mixed traffic routes, and demonstrate how the benchmark for possession time for track inspection can be reduced by up to 75%'.
Objective 4 was 'to develop modular infrastructure components and subsystems'.
Objective 5 was 'to develop a new maintenance planning and scheduling tool that is able to optimise the programme of required maintenance activities, taking account of the benefits brought about by other improvements in the AUTOMAIN project. The tool, together with the other individual subsystem level improvements will reduce the overall benchmark possession time by 40%'.

The results of these objectives have been previously been quantified in the innovations section of this report. However, additionally, WP6.2 aimed to address the following functional requirements. The table below shows the details of these requirements, and a summary of how WP6.2 has addressed these requirements:

Functional requirement ID	FR01
Capability Requirement ID	CR01
Functional requirement	To be able to collect performance and condition data using automated methods.
Source	WP3, WP4
Validation	The WP's have to show that their data collection process is fully automated.
Performance	No human interaction is needed in collecting data and disclosure of data to the user.
Constraints	Not relevant for manual measuring methods.
Verification	In WP6
Comments	By avoiding human interaction in the data collection process, the chance of introducing mistakes is diminished, the continuous availability of data is improved and the costs of data collection can be reduced.
WP result	Within DS2 is has been shown that: - The overhead camera innovation has the ability to allow maintenance staff to remotely check for the presence of components, thus reducing (or

	eliminating) the need for works to enter the track; - Accurate switch geometry data can be collected using a train-borne system that eliminates the needs for works to access the track. This is mainly considered to be an effective solution for large groups of switches; - For individual switches the hand-held measurement system improves switch geometry and gauging accuracy and removes not deterministic nature of existing method. This approach also reduces the length of time that personal need to spend on the track.

Table Y; Description of functional requirement 1 and its results in DS2 (source D.1.1).

Functional requirement ID	FR08
Capability Requirement ID	CR08
Functional requirement	To be able to use recorded loads applied to the track.
Source	WP3 (T3.2)
Validation	WP shall show the results of the measurements.
Performance	Accuracy of the measurement has to be defined in the WP.
Constraints	Track only.
Verification	WP6
Comments	Cumulative load is expected to be a main indicator for preventative maintenance and quality assessment. Several systems such as Gotcha, DafuR and others are already in use. Same load but different settlement in the track of the switch results in different lifetime and “health”.
WP result	Within DS2 the ability to measure and record the deviation from the present gauge measurements (rather than simply a pass/fail measurement, as is currently done), offers the ability for the first time to monitor the degradation of switches as loads are applied to the track.

Table Z; Description of functional requirement 8 and its results in DS2 (source D.1.1).

6. Functional requirements.

This section of the report relates the functions that were developed to guide the efforts of the work packages, to the project objectives and the work packages' findings.

Section 1 of this report has introduced the three-stage approach used by the project to increase track maintenance efficiency and improve availability of freight train paths. Stage 1 was seen as being relatively easy to achieve compared to the other two, while stage 3 was seen as potentially being the most difficult. As a result it was assumed that the technology and process changes required for each stage would not occur in the same time scales. It was further assumed therefore, that the time horizons for achieving each stage should be: Stage 1 – 2026; Stage 2 – 2036; and, Stage 3 - 2051

The three stages describe the essential mission of the project, but not the underlying user functional requirements. It was recognised during preparation of the original submission to the European Commission, that further elaboration of the mission would be required to help focus the efforts of the work packages. Therefore, Work Package 1 did some work to identify supporting sets of requirements for each of the three stages. The results are shown in Table AA, and described in more detail in D1.1.

Stage	Requirement	Simplified Requirement
1	To be able to collect data using automated methods	Data collection
	To be able to transmit data rapidly	Data collection
	To be able to process and disclose data within 24 hours	Data processing
	To be able to collect and measure data at line speed	Data collection
	To be able to renew track components easily	Rapid maintenance
	To be able to predict trends in track degradation	Data processing
	To be able to package work	Work packaging
	To be able to record loads applied to the track	Data collection
	To be able to reference all track condition data	Data collection
	To be able to access work sites rapidly	Site access/egress
	To egress work sites rapidly	Site access/egress
	To be able to carry out reactive maintenance rapidly	Rapid maintenance
	To be able to plan on the basis of low levels of reactive maintenance	Work packaging
	To achieve low frequencies for planned maintenance	Design
	To have low track renewal frequency	Design
2	ICT supported access regimes	Site access
	To be able to have real time data processing	Data processing
	To be able to have instant access to processed data	Data processing
	New switch and crossing designs	Design
3	Embedded knowledge and rules in objects and control systems	Design
	Optimise scheduled activities	Work packaging

Table AA; List of requirements and simplified requirements related to project stage.

Section 2 of this report has described the interface between the project objectives and the work packages (see the diagram of Figure 3). To link the functions to the objectives and work packages the

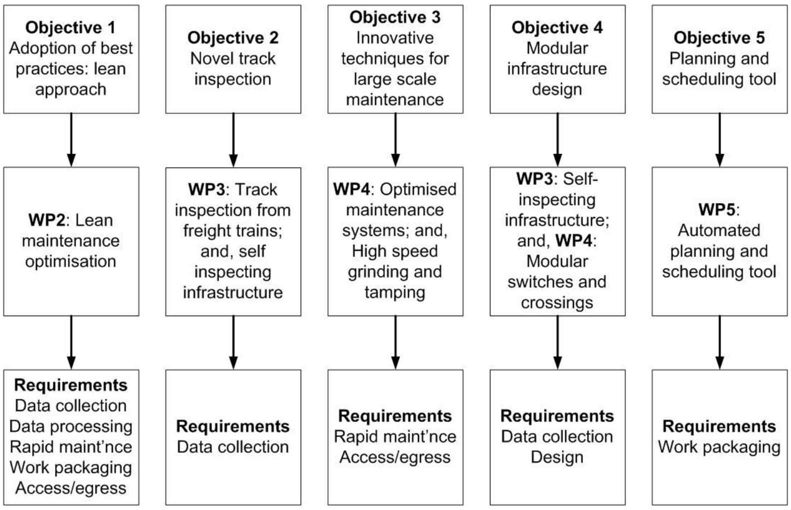

Figure 13; Diagram showing simplified requirements related to objectives and work packages.

diagram was developed further: firstly, the twenty-one requirements were synthesised and simplified into six higher level requirements to make the linkages easier to understand (see Table AA); and, secondly, the simplified requirements were allocated to the appropriate objectives. The results of this exercise are shown in the diagram of Figure 13.

In Objective 1, WP2 carried out lean analysis exercises with a number of infrastructure managers, to identify best practice across the full range of requirements. The results showed a theoretical possible saving in possession time for tamping of 58%; and, a more realistically achievable saving of 34% if best practice was adopted. For grinding activities, the realistically achievable saving based on best practice was 27%.

The research showed that to achieve these savings, further work will be required on future projects relating to a number of the requirements. These are:

- Starting possessions on-time (access/egress; work packaging);
- Keeping the amount of unproductive time incurred moving equipment from work site to work site to no more than 17% (work packaging);
- Ensuring that, in the case of tamping, the tamper already has the track's design alignment programmed in before work starts (data collection; data processing);
- Ensuring that tamping and grinding activities will not be disrupted by other maintenance activities within the possession (work packaging);
- In the case of tamping, ensuring that the correct type of tamper, and a crew with the necessary skills, are provided (rapid maintenance); and,
- Ensuring contingency provided in the programme is not too large (rapid maintenance team arrivals; work packaging; access/egress)

In Objective 2 WP3 has addressed the requirement for data collection in five broad switch and crossing areas: visual inspection using a pantograph-mounted, overhead camera; geometry measurement using hand-held and/or train-mounted equipment; component measurement using hand-held equipment; and, non-destructive testing using equipment mounted on a specialist inspection trolley. The issue of tightness and security of switch and crossing components has been addressed through the development of 'smart washers' that sense the amount of torque remaining in a bolt and provide information to a central monitoring point. Automated monitoring of point machine data was found to be impractical; and, it was decided that a better approach would be to design more robust point machines with better long-term performance.

In Objective 3, WP3 contributed to the requirements for access/egress by suggesting technologies that utilized on-train monitoring techniques. In this way, the need for a between trains possession was removed. In cases where the need for possessions could not be removed, WP4 addressed the requirement through development of an algorithm to support maintenance between trains. It can find the optimal maintenance window for corrective (reactive) maintenance, such as small track geometry failures (manual tamping), S&Cs failures, or any infrastructure failure that needs maintenance within a short time period, e.g. 24 hours.

In Objective 4 WP3's work for Objective 2 applies to the requirement for self-inspecting infrastructure. WP4 has addressed the design requirement through the use of systematic root cause analysis for spot or local failures. An improvement methodology has been developed, called the 'Link and Effect' model, which focuses on performance measurement for improved planning of railway maintenance, while at the same providing performance data that can feed into better infrastructure designs.

In Objective 5, WP5 has addressed the issue of work packaging with the development of a tool that allows the insertion of maintenance activities between train paths, while ensuring that commercial traffic is not affected. The tool has been demonstrated to produce potential savings of between 6% and 15%. The saving corresponds to the difference in possession time between a plan generated with basic planning rules, and an optimised plan generated with the help of simulated annealing optimisation techniques.

With regard to the work packaging requirement, WP5 has shown how savings in possession time can vary depending on which criteria are used in the analysis: for example, the distance travelled by machines, which relates to the access/egress requirement covered by WP2 and WP3; the gap between scheduled dates and target dates for operations, which relates to the data gathering and processing requirements of WP2, and the design requirement of WP4; or, the impact on commercial traffic, which relates to WP5's own work packaging requirement.

The tool developed by WP5 integrates output from the data collection and data processing requirements. It directly addresses the access/egress requirement by computing the shortest paths for maintenance trains between operations and between operations and depots, so that work sites can be accessed as soon as possible. The research also shows that for work packaging to be successful, the maintenance activities in the package must be technically and operationally compatible.

7. Overall evaluation, conclusions and recommendations.

7.1. Overview of results.

Based on the information shown in the preceding chapters Table BB and Table CC show overviews of the AUTOMAIN results in terms of the original criteria. The calculated results show a remarkable range. During the research it was found that the eventual effects depend very much on the locally existing technology and the nationally applied strategies. The calculation of the results thus leads to a certain range and not to an exact number. While writing the proposal this knowledge was not available. The original objective should be considered as a best guess of what could be achieved.

KPI	Objective	Maintenance task influenced by objective	Effective objective	Result	Effective result
1	50%	maintenance (key task), large scale maintenance (key task)	15%	43% - 47%	13% - 14%
2	75%	Inspection	14%	63% - 66%	12%
3	25%	large scale maintenance (key task), large scale maintenance	3%	38% - 41%	4% - 5%
4	50%	Future effect	-	unknown	unknown
5	Leading to 40% overall	all maintenance tasks	8%	6% - 15%	4% - 10%
Total result	40%		40%		**33% - 41%**

Table BB; Overview of AUTOMAIN results in terms of the KPIs.

Innovation	1 Analysis methodology.	2 Higher performance inspection	3 Higher performance maintenance	4 Modular components	5 Planning and scheduling.
KPI	✓	✓	✓	?	✓
Comments:	43-47%	An improvement of 63-66% has been shown, where 75% was the objective.	38-41%		6-15%.
Primary objective	✓	✓	✓	?	✓
Final TRL	✓	✓	✓	?	✘
Comments:	TRL9, where the objective was TRL8.	Depending on the developed technique between 2 and 9.	TRL 6-8		TRL4 reached. TRL 7 turned out to be too ambitious in the scope of the program.
Critical success criterion	✓	✓	✓	?	✓
Comments:		Demonstrated in WP6.			

Table CC; Overview of AUTOMAIN results in terms of the innovations.

7.2. Main conclusions.

1. The AUTOMAIN program shows to have reached its quantitative objectives. In total the developments and innovations within the program indicate that a possession time reduction between 33 and 41% is achievable.
2. The goal of objective 1 has been met by applying lean analysis techniques in a railway maintenance environment and showing that on the long term possession for key tasks be reduced by 43-47%.
3. Possession time for inspection can be reduced by over 60% by applying the developed techniques such as overhead cameras, train-borne S&C inspections and hand-held inspection devices.
4. Large scale maintenance tasks can be optimised by applying some of the developed innovative approaches such as combining grinding machines, fast slag collection and high speed grinding combined with conventional grinding, leading to a reduction in possession time up to 41%.
5. Modularisation of creates interesting design options such as the movable blade, although in this stage of the developments it is not possible to estimate the effect on possession times.
6. Applying novel algorithms and planning techniques shows a possibility to reduce maintenance possession times by almost 15% simultaneously optimising travelling times of machinery and costs.
7. The eventual results and their achievability depend strongly on (1) the national maintenance strategy, (2) the developments in work organisation that have been realised earlier and (3) the success of necessary future technical developments.
8. The exchange of knowledge between partners should be considered as part of the innovation process. Existing technology in one country turned out to be the innovation in another. For that reason some of the innovations mentioned by the WPs could be considered existing technology and therefore, not really innovative: for example, high speed tampers and grinders. The innovative part in the research often covered the application of those existing technologies and the disclosure of their benefits in a clear defined way.

7.3. Recommendations.

9. Railway managers as well as other involved companies are advised to consider in what way the AUTOMAIN results can be made applicable in their situation. Only then the real results can be booked.
10. The field of data management and exchange of data is recommended as interesting for further research. One obvious problem has been the availability of data on which to base the research. Obtaining a data set which is consistent across a range of IMs, which is consistent across a range of IMs, is a well-known problem. The university of Luleå already took the initiative to start further research on the topic of data management for maintenance (see §3.4.1).
11. The further development of RailML as a common standard for information exchange has been touched in AUTOMAIN but shows promising possibilities for future research.

12. The developed planning system shows interesting perspectives for further development. Some parties (including the University of Braunschweig) are already preparing further work based on the foundations built by AUTOMAIN.

7.4. Conclusions and recommendations concerning the process of innovation programs.

13. The AUTOMAIN choice to organise dissemination sessions on a national level instead of a big central seminar resulted in a very effective dissemination process. It gave the opportunity to tune the presentations to nationally applicable and appealing examples. And it also made it possible for many interested people to join as the meetings were nearby and easily accessible. This dissemination approach is recommended strongly for other European programs.
14. The idea of setting up the program according to SE-principles is good. By using this approach consistently during the program, the ultimate objectives are well defined and evaluations and verifications can be done.
15. The demonstrators in WP6 had been defined to show the effect of all developments coming together. Here the “system-level” should become visible. In practice the demonstrators appeared to be rather focused on a specific development (inspections). By taking time in an early stage to define the demonstrators more precisely they will show the results on the expected level.

Appendix A. **Overview of the publications (deliverable reports).**

Deliverable	Title	Dissemination level[11]	Publication date
D1.1	Market and customer requirements for the project	PU	31 Oct '11
D1.2	Description of Demonstration scenarios and evaluation criteria	PU	31 Jan '01
D1.3	Evaluation of performance impact of AUTOMAIN solutions	PU	31 Jan '14
D2.1	High level breakdown of maintenance activities	PU	29 Sep '11
D2.2	High level breakdown of maintenance activities	PU	15 May '12
D3.1	In-service inspection measurement algorithms	PU	24 Dec '13
D3.2	Potential for self-inspecting infrastructure	PU	13 Oct '13
D4.1	Improvements analysis	PU	Pending28 Jan 14
D4.2	Optimised maintenance activities	PU	Pending28 Jan 14
D5.1	Planning and scheduling tool for optimized maintenance	PU	31 Jan '13
D5.2	Tool in operation for demonstration of results	PU	Pending29 Jan 14
D6.1	Demonstration of in-service inspection by a freight locomotive	PU	Pending31 Jan 14
D6.2	Demonstration of modular, self-inspecting switch technology	PU	Pending31 Jan 14
D7.1	Project website	PU	4 Jul '11
D7.2	Dissemination, exploitation and training plan	RE	19 Sep '11
D7.3	Dissemination, training and Exploitation progress and evaluation report	PU	11 Mar '13
D8.1	Project Initiation Document	RE	4 Jul '11

All deliverables marked as "PU" are available on the public part of the program's website: www.automain.eu.

[11] PU: Public, RE: restricted to a group specified by the consortium (including the Commission Services).

Appendix B. Tabular overview of the relations between WPs, innovations and objectives.

	Objectives					Work packages						Innovations				
PIs	O1	O2	O3	O4	O5	WP2	WP3	WP4	WP5	WP6-1	WP6-2	1	2	3	4	5
1. KPI_1 = (1 – possession time required for maintenance using innovation / today's required possession time for maintenance) x100%.	X					X						X				
2. KPI_2 = (1 – possession time required for inspection using the novel approach/ today's required possession time for inspection) x100%		X					X						X			
3. KPI_3 = (1- total possession time required for maintenance using innovative techniques/ today's required possession time for maintenance) x100%			X					X						X		
4. KPI_4 = (1- possession time required after using modular elements/ today's required possession time) x100%				X			X	X							X	
5. KPI_5 = (1 – possession time needed when using innovative scheduling tool/ today's needed possession time) x100%.					X				X							X
Work Packages																
WP2: analysis and lean optimisation	X					X						X				
WP3: High speed inspection		X		X			X						X	X	X	
WP4: High speed maintenance.			X	X				X					X	X	X	
WP5: Automated planning and scheduling					X				X							X
WP6: Demonstration DS1											X	X	X			X
WP6: Demonstration DS2											X	X	X		X	X
Innovations																
1. A new methodology for analysing and optimising maintenance processes by applying best practices from other industries.	X					X				X	X	X				
2. Higher speed infrastructure inspection.		X					X	X		X	X		X			
3. Higher speed track maintenance.			X				X	X						X		
4. Modular infrastructure components and subsystems.				X			X	X			X				X	
5. The improvement of automatic maintenance scheduling and planning systems.					X				X	X	X					X

Appendix C. **List of figures and tables.**

Figures: **Page**

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