AUTOMAIN

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

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D1.2: Description of demonstration scenarios and evaluation criteria.

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Document Summary Sheet

As a second phase in WP1 of AUTOMAIN, it was planned that the relevant KPIs and evaluation criteria for the project would be defined. Simultaneously, the relevant scenarios for the demonstrators (WP6) and the requirements for the planning tool (WP5) have been developed. Based on the requirements as published in D1.1, these elements have been worked out. The result of this work is described in this report.

The main objective of this part of WP1 is to develop the verification and validation references in order to be able to verify the results of the project in the latest phase.

This document is the report covering deliverable D1.2.

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V2	11 Jan 12	Contributions added	Different contributions from LTU, SNCF and UoB added.
V3	13 Jan 12	Updated	Updated contributions from LTU and SNCF after the conference call d.d. 12/1/12 added. Introduction rewritten. Chapter about demo scenarios moved forward (was Chapter 5). Tables in app. B&C combined to one.
V4	16 Jan 12	First draft for PMT	Updated contribution of UoB (in Chapters 3 and 4) and LTU (Chapter 2). Chapter 7 written and tables in 1.1 and 7.1 introduced. App. E introduced.
V5	20 Jan 12	Updated.	Adapted according to the first comments of the PMT.
V6	26 Jan 12	Updated	Chapter 2 completely rewritten based on the discussions in the PMT on 23/1/12. Chapter 4 rearranged.
V7	27 Jan 12	Updated	Chapters 5 and 6 revised and completed. Some modifications in Chapter 2 following the PMT-discussion on 27/1/12. Executive summary added.
V8	28 Jan 12	Updated	Chapter 3 revised and completed. Chapter 4 merged with Chapter 3. English corrected throughout the document.
V9	30 Jan 12	Final draft	Chapter 4 (planning tool) revised. Formulas in Table A adapted. Table I completed.
V10	31 Jan 12	Final version	All changes accepted. Foot-notes 6 and 7 added. Explanation of TRL added in list of abbreviations.
V10A	6 Feb 12	Final version	Some minor textual corrections (footnote 9, section 4.6.1)

Table of Contents

Executive summary

This report describes the results of the work done in task T1.2 within work package 1 (WP1) of AUTOMAIN. The overall goal of WP1 is to set the functional requirements and objective functions of the project.

Report D1.1 was published earlier and contains a set of functional and capability requirements that are assigned to the different work packages. For T1.2 these requirements have been taken as a starting point, together with all information in the DoW concerning objectives and innovations.

By using existing research results and earlier EU-funded projects (e.g. InteGRail and Innotrack), the basic elements of railway capacity have been identified. The scope of AUTOMAIN has been set such that the project does not focus on increasing capacity directly, but aims at enlarging capacity by reducing the required possession time for maintenance. The AUTOMAIN objectives are, for that reason, all defined in terms of (reduction of) required possession time. More precisely:

*The **high level aim** of the proposed project is to make the movement of freight by rail more dependable (reliable, available, maintainable and safe) through the generation of additional capacity on the existing network. Through the widespread introduction of automation that is designed to improve the Reliability, Availability, Maintainability and Safety (RAMS) of railway infrastructure equipment and systems, it is anticipated that required **possession time (downtime) of the railway could be reduced by as much as 40%**.*

The derived objectives from this overall target are:

1. Adopting best-practices and lean approach: possession time for key maintenance tasks can be reduced by up to 50%.
2. Novel track inspection approach: Possession time for track inspection can be reduced by up to 75%.
3. Adoption of innovative techniques for large scale maintenance. These technologies can reduce the benchmark possession time by up to 25%.
4. Modular infrastructure design: These technologies can reduce the benchmark possession for installation, maintenance and inspection during the life of the asset by up to 25%.
5. Better planning and scheduling, using a tool. The tool will, together with the other individual subsystem level improvements, reduce the overall benchmark possession time by 40%.

All objectives and work packages have been brought together in a way that shows their interdependencies.

As a result of the work done in task T1.2 within work package 1, the evaluation of the future results of AUTOMAIN has been defined more precisely. The following ways of evaluation have been set:

- For each objective of AUTOMAIN a quantitative performance indicator has been defined. At the same time, the WP which contributes to the specific result for each objective has been indicated.
- For all intended innovations, ways of evaluation have been set, eventually combined in an evaluation matrix.
- For each demonstrator (WP6), the part of the solution which has to be demonstrated has been indicated.

- For the planning and scheduling tool, more specific requirements have been defined.

These instruments will help the WPs to define their derived objectives and the way to verify them. Altogether these instruments will also facilitate the overall evaluation of the results of AUTOMAIN at the end of the project.

Based on the results of this task, T1.2, each WP has to define what elements (PIs, CRs, and objectives) are relevant for their work. In each WP, activities have to be introduced in the working program to collect the necessary information and to ensure that the required data and PIs can be reported. **Each WP-report will have to contain a paragraph describing the results in terms of the PIs, CRs and objectives defined in this report and in report D1.1.** Within WP1 all results will eventually be gathered and an overall evaluation of the project will be made.

List of abbreviations and acronyms.

BRMS	Business Rules Management System
CdM	Condition Monitoring
CMMS	Computerised Maintenance Management System
CR	Capability Requirement
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 3.3 and 3.4)
DynPP	Dynamic Planning Problem, also referred to as problem 4.
ERM	Enterprise Resource Management
FR	Functional Requirement
GUI	Graphical User Interface
KPI	Key Performance Indicator
KRA	Key Results Area
ICT	Information and Communication Technology
IM	Infrastructure Manager
IT	Information Technology
LSCO	Large-Scale Combinatorial Optimisation
LTPP	Long-Term Planning Problem, also referred to as problem 3.
MPI	Maintenance Performance Indicator
JSSP	Job-Shop Scheduling Problem
PDD	Problem Definition Document
PI	Performance Indicator
POC	Proof of Concept
PSD	Problem Solution Document
SE	System Engineering
SLA	Service Level Agreement
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
TWIP	Time Window Insertion Problem, also referred to as problem 1.
WO	Work Order
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 five concepts approach to increasing the availability of freight train-paths. The first step change (from concept 1 to 2 in Figure 1) aims to reduce current night-time maintenance track closures through the application of best-practice maintenance technologies and procedures. The second step change investigates the development of innovative techniques to facilitate maintenance during the day, in short possessions between trains.

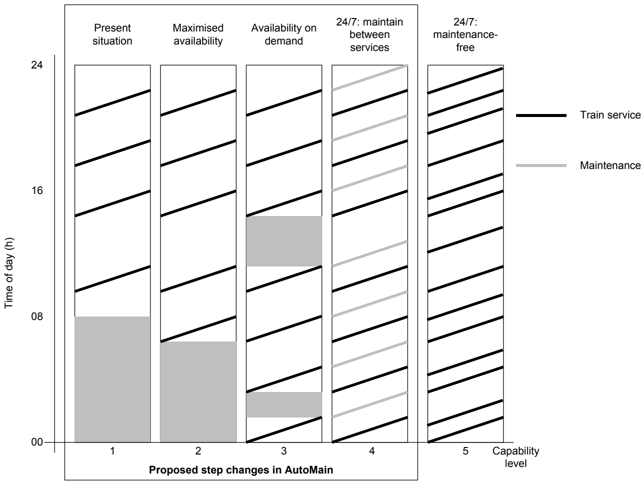


Figure 1; The five operating concepts defining the AUTOMAIN research objectives.

Finally, the third explores the development of radically new techniques and procedures to facilitate maintenance at line speed. 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.

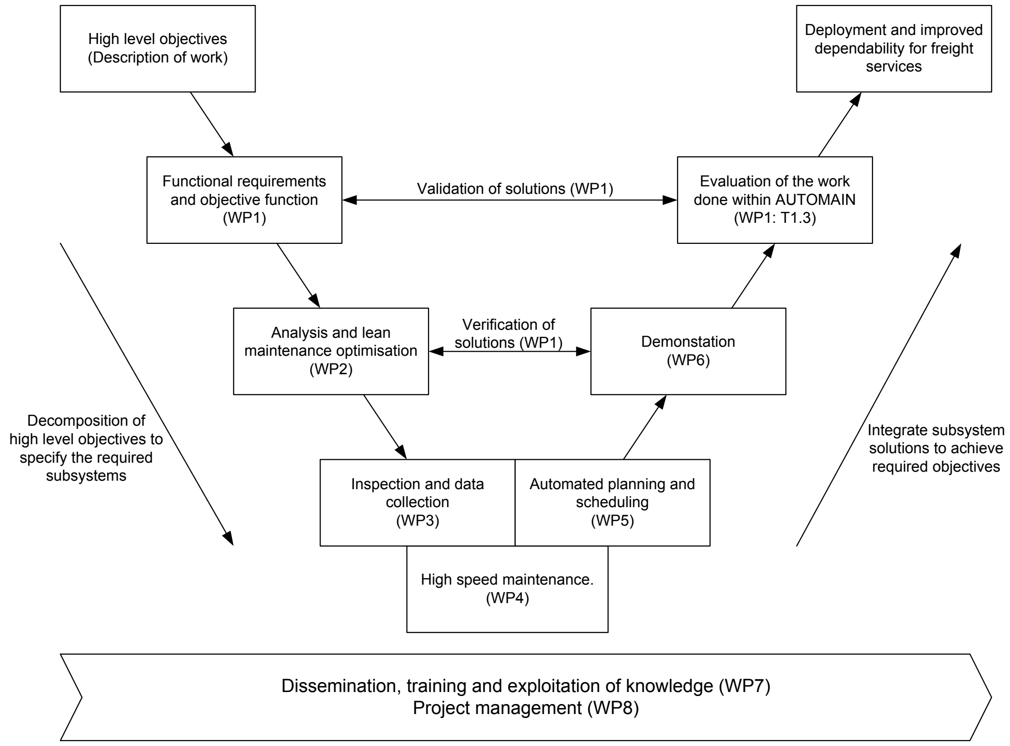


Figure 2; The SE-structure as used within AUTOMAIN.

1.2. Work done in AUTOMAIN to date.

As part of the first work package (WP1), a significant amount of work has been done to define the end-user requirements for the AUTOMAIN results. This has been done at an early stage of the project to ensure that the results will meet the overall goals of the EU seventh framework programme and the original project's offer.

In order to define these specifications, a state-of-the-art survey has been made, future developments have been discussed and formulated and functional requirements have been derived from this work. The requirements have been written in the first deliverable of work package 1 (D 1.1, *Market and Customer Requirements for Planning and Scheduling, Faster Maintenance and Faster Inspection*), as published on the website[1].

One of the main results of D1.1 is the set of functional requirements (FRs). These FRs have been translated into capability requirements (CR), indicating more precisely what requirements the

[1] www.automain.eu

systems AUTOMAIN is going to deliver will have to meet. An overview of these requirements can be found in Appendix A. In this D1.2 report, they will be referred to by CR and the relevant number. As the report deals with the resulting systems, it will only refer to CRs, although CRs and FRs are numbered identically and have a one-to-one relation.

1.3. The objective of this report.

This deliverable D1.2 contains the evaluation and verification methods of AUTOMAIN. Its main objective is **to show the way the results of the other work packages, as well as the results from the project as a whole, will be verified and evaluated**. In system engineering terms, it can be stated that D1.2 describes the evaluation and verification methods which are used within AUTOMAIN. More precisely, the report indicates how we evaluate whether the proposed innovations have been developed sufficiently and how we measure if the developed techniques, working methods and systems have contributed to the project's objective.

In accordance with the DoW[2], this report contains:

- Report of product acceptation criteria for the other WPs (excluding WP8 Coordination). This document is the input specification for WP 2,3,4,5,6 and 7; it also sets the evaluation criteria (KPIs) and a methodology for assessing the innovations developed within the AUTOMAIN project.
- Specification document for the scheduling and planning tool (WP5).
- Definition of detailed scenarios for demonstration.

Based on the work done to create D1.1, the defined requirements will be "translated" in a way such that the other WPs can deliver what is expected.

The following will be developed and reported:

- An overview of relevant performance indicators (PIs). These PIs will include a mathematical cost[3] function. The mentioned PIs will define performance goals for efficient and high speed maintenance.
- An evaluation framework, based on the KPIs, that will provide evaluation of each innovation and hence demonstration scenario.
- The project and end-user specifications for the planning tool to be developed in WP5.
- The detailed scenarios that will lead the work to be done in WP6 (demonstrators).

1.4. Contents of this report.

In order to verify that all AUTOMAIN results are linked, a sequence of results has been defined. This sequence starts with the main critical results of the project and eventually leads to the measurable evaluation criteria. Referring to the need for more freight capacity (ref. § 1.1), the main result should

[2] 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.
[3] The term "cost" in this statement does not necessarily refer to costs in Euros, but shows the necessity to have KPIs that are quantitative rather than qualitative.

be an increased capacity on the track. Within AUTOMAIN, this increased capacity is reached by creating more availability of the network. So the decisive issue is: **Did we succeed in creating more availability?**

Referring to the operating concepts in the project's results (Figure 1), this question can be reformulated per stage:

Concept 2: Are we able to do the work in less time within the current timetable?

Concept 3: Can we break the maintenance work into big chunks?

Concept 4: Can we split the work into real small blocks that fit within the planned timetable?

Based on these questions and the other objectives mentioned in the DoW, high level indicators will be developed to identify the results. These indicators will form the set of relevant performance indicators (PIs), to be discussed in **Chapter 2.** The PIs offer a way to judge quantitatively to what extent the AUTOMAIN results meet the original objectives. The AUTOMAIN results will also be assessed to establish the effectiveness of the created innovations. This will be done by a set of evaluation criteria that are described in **Chapter 3.** The set of PIs will be linked to the evaluation criteria as far as is feasible. In this way the evaluation can also be done quantitatively, although some aspects will probably be judged in a qualitative way. The so-called evaluation matrix can be considered as the horizontal line in the SE-approach that links the "left side" requirements to the "right side" results.

The sixth work package of AUTOMAIN, the demonstrators, aims at showing the overall results of the project and their applicability. During these demonstrations, the main results of the project have to be made clear. For that reason, in this report the detailed scenarios of the demonstrators will be summed up in **Chapter 3, Paragraph 3.2 and further.** The definition of these scenarios clarifies at an early stage what AUTOMAIN wants to show and prove.

As a separate result, within AUTOMAIN the principles of an advanced planning and scheduling tool will be developed. The results of this tool will be difficult to evaluate according to the PIs and evaluation matrix. Moreover, this tool uses many results of the earlier developed working methods and systems. The project and end-user specifications of this tool will therefore be mentioned separately in **Chapter 4**. Nevertheless, an attempt is made to connect the requirements of the planning tool to the relevant PIs.

The information necessary for the evaluation and verification of the results will be delivered by the different WPs. The work of each WP will be finalised with an overview of results that aims to meet the PIs and evaluation criteria as defined in this report. In order to verify its applicability, a review of this report has been done by the WP-leaders. Their main comments are summed up in **Chapter 5**.

Finally, in **Chapter 6**, some overall conclusions are drawn. This chapter also contains a tabular overview of all defined PIs, criteria and other relevant aspects and their correlations.

2. The relevant high-level performance indicators.

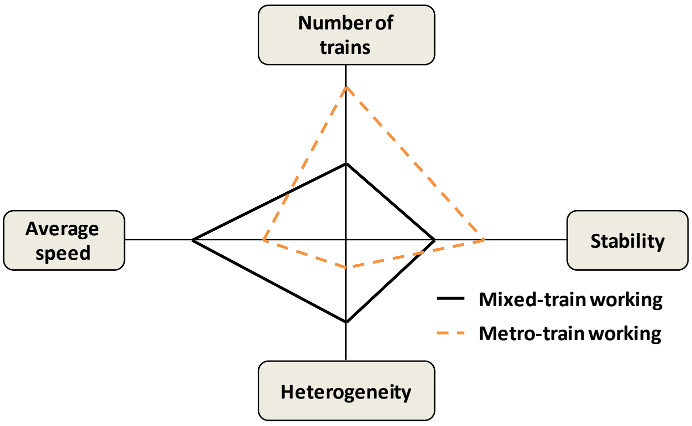
The goal of AUTOMAIN is to increase freight train capacity by reducing track possession time for infrastructure maintenance. In order to verify the effects of the project, in this chapter the relevant indicators are explained. By analysing the main elements of capacity, the AUTOMAIN objectives are explained and their verification is defined.

2.1. Railway capacities.

The capacity of railways is a complex aspect of the system that is difficult to define. Many technical, operational and organisational factors will affect the overall capacity and are not always unambiguously defined. According to UIC Leaflet 406, capacity as such does not exist; it depends on the way it is utilised. On a given infrastructure, capacity is based on the interdependencies existing between:

- the *number of trains* (per time interval, e.g. trains per hour). When train intensity increases, less capacity is left for quality, as expressed in the parameters described below;
- the *average speed*. The braking distance increases proportionally more than the average speed;
- the *stability*. Margins and buffers have to be added to the running time of trains and between train paths to ensure that minor delays are suppressed instead of amplifying and so causing (longer) delays to other trains;
- the *heterogeneity*. When the differences in running time between different train types worked on the same track are great, similarly the capacity consumption of the same number of trains will increase proportionately.

The relation between these parameters is clearly shown in the "capacity balance", as illustrated in Figure 3. In this qualitative model, an axis for each parameter is drawn from a unique origin. A chord links the points on the axes, corresponding to the value of each parameter. The length of the chord represents *the* capacity. Capacity utilisation is defined by the positions of the chord on the four axes. Increasing capacity means increasing the length of the chord.[4]



The conclusion that capacity as such does not exist leads to further investigations in order to define in what way it will be possible to measure the AUTOMAIN results in terms of the original objective.

Figure 3; The balance of railway capacity. Adapted from (UIC, Code 406).

[4] The main part of the text in this paragraph is quoted from UIC406.

2.2. Elements of capacity.

Within the research project InteGRail, work has been done to define a railway-business KPI-tree (see Figure 4). The aim of this tree was to show how different actors and activities are interrelated, and how they all affect the overall capacity. Although the InteGRail tree ends in passenger transport, a similar tree could be made up for freight.

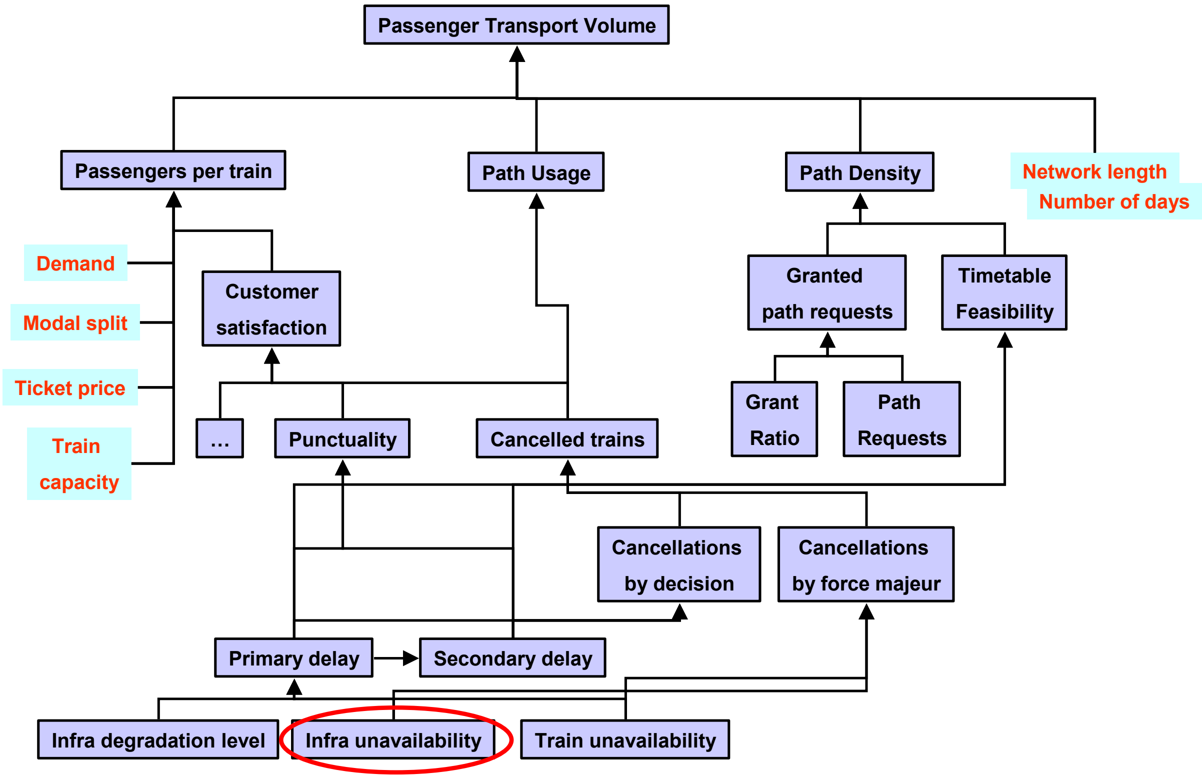


Figure 4; The InteGRail KPI-tree.

Taking a closer look at the InteGRail KPI-tree, it can be seen that the majority of the elements mentioned are out of the scope of AUTOMAIN. Only at the bottom “Infra unavailability” can be regarded as the major element to be affected by AUTOMAIN. As AUTOMAIN deals with the reduction of the capacity used due to maintenance, it affects the overall availability. How this capacity will be used (e.g. for freight or passengers and with what effectiveness) is the result of the multiple actors and stakeholders within the railway system.

The indicator “Infra unavailability” has been determined further. The elements affecting this are shown in Figure 5. The most direct way to affect the Infra unavailability is by improving the activities that are counted under “planned”. This is what AUTOMAIN is aiming at: a reduction of the necessary

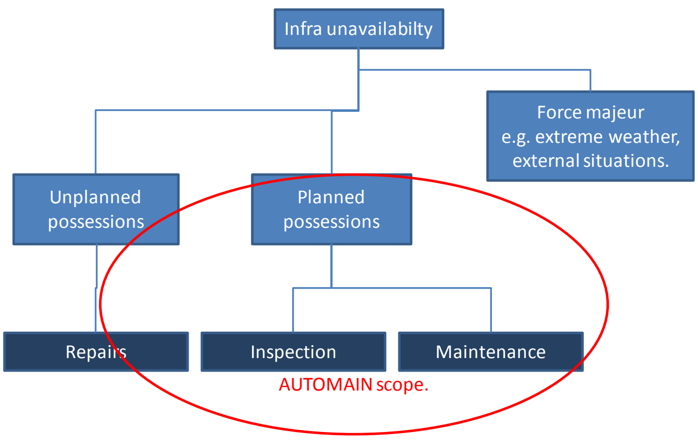


Figure 5; Elements of Infra Unavailability.

possession times for maintenance, by improving the planning process and the activities to be planned.

Of course, the ultimate improvement would be to reduce the need for maintenance. The actual railway system, however, uses technology that is not maintenance-free and a higher occupation will lead to even more required maintenance. The EU-project SUSTRAIL[5] is searching for improvements in this area. AUTOMAIN focuses on planned possessions only, as unplanned activities can be controlled and reduced through effective and improved inspection and planning/scheduling leading to a more reliable network. However, it should be realised that a more concise and complex planning also leads to a higher dependency on the work processes and machines, potentially leading to a higher risk of not meeting the original planning.

Having made this analysis, **AUTOMAIN has formulated its objectives in terms of a reduction of possession time for maintenance by 40%.** The objectives are not defined in terms of (freight) capacity or number of train paths, as there are too many other factors affecting that result. By reducing the necessary possession times for maintenance, a major contribution to the reduction of unavailability and thus to the improvement of overall capacity will be realised.

Although 40% is to be regarded as a major reduction of possession times, it should be mentioned that this has only a relatively small effect on the total capacity. Figure 6 (from UIC 406) shows the different elements in the calculated capacity. The AUTOMAIN target refers only to the part indicated *d)* in the figure.

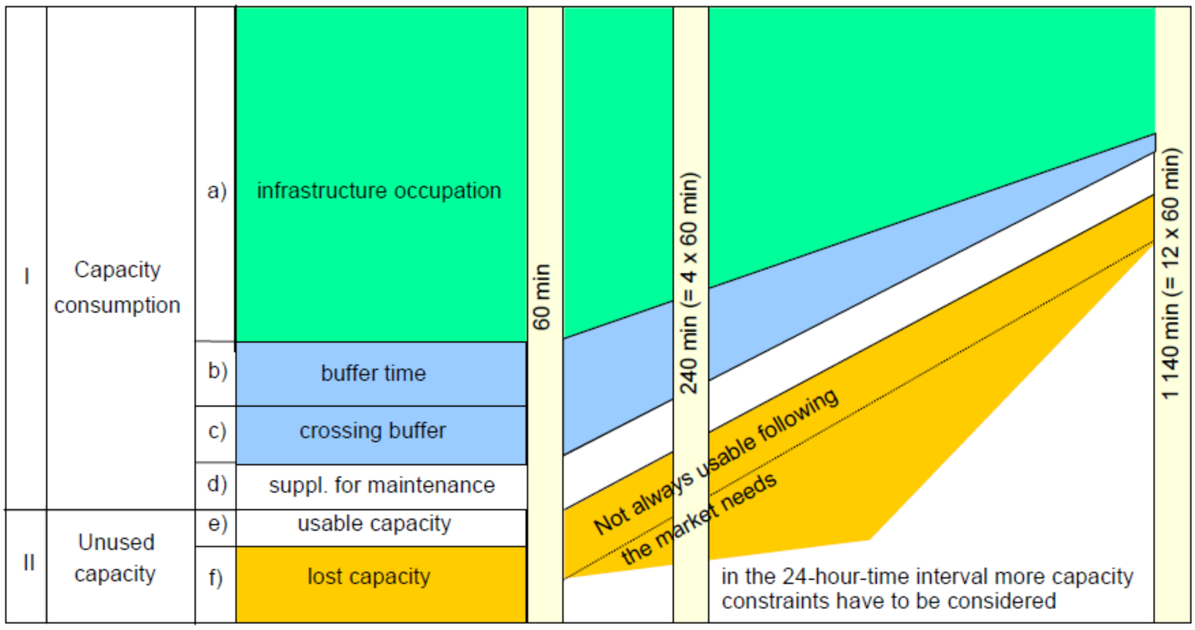


Figure 6; Elements of infrastructure capacity according to UIC 406. (For further explanation refer to UIC leaflet 406).

[5] Refer to www.sustrail.eu.

2.3. AUTOMAIN objectives and the work packages.

In the DoW that was issued in the proposal phase of the project, some clear objectives have been set. The main objective is formulated as:

> *The **high level aim** of the proposed project is to make the movement of freight by rail more dependable (reliable, available, maintainable and safe) through the generation of additional capacity on the existing network. Through the widespread introduction of automation that is designed to improve the Reliability, Availability, Maintainability and Safety (RAMS) of railway infrastructure equipment and systems, it is anticipated that required **possession time (downtime) of the railway could be reduced by as much as 40%**.*

In §2.2 it has already been mentioned that this is the ultimate objective of AUTOMAIN.

The DoW also contains more specific objectives, all in some way or another contributing to the overall result. Each of these sub-objectives can be linked to the work packages of AUTOMAIN and are realised by these work packages. Figure 7 (derived from figure B1.7 in the DoW) shows how the objectives and the WPs are interrelated.

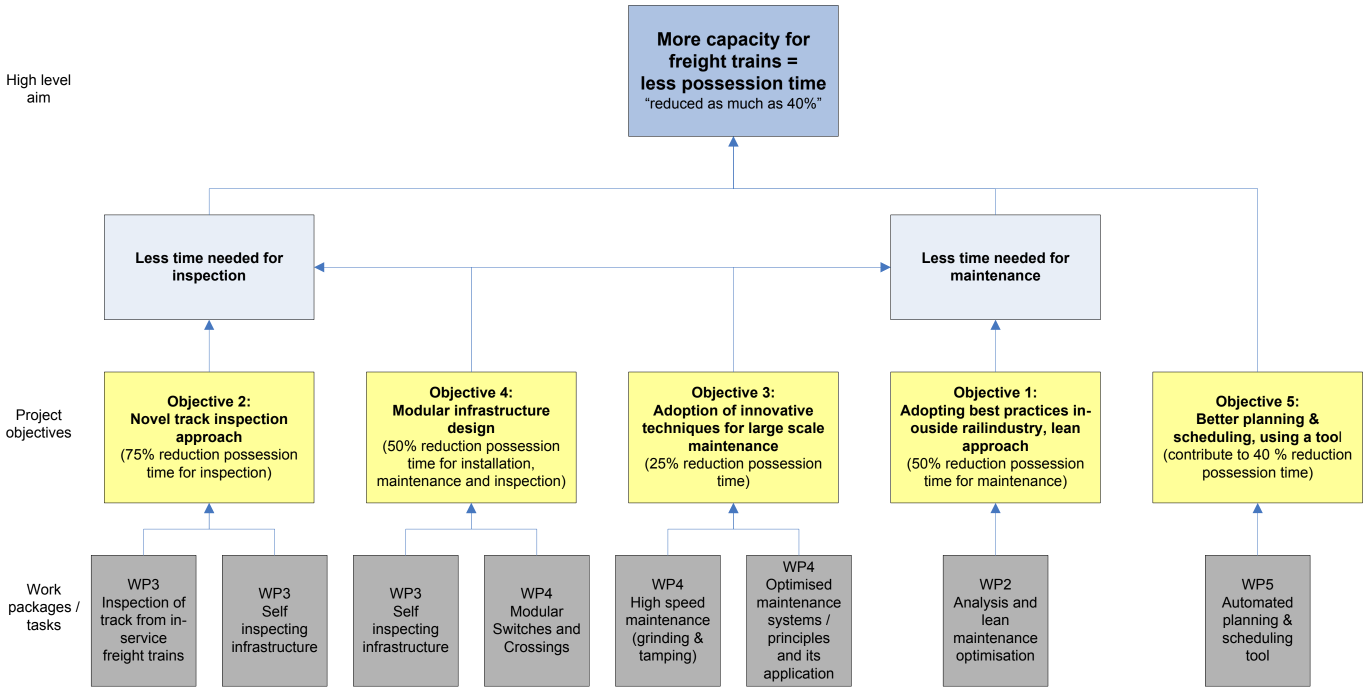


Figure 7; An overview of the AUTOMAIN objectives and work packages and their interrelations.

2.4. How to measure the results.

The AUTOMAIN consortium has formulated the ambition to prove the level to which the objectives are met by the results of the project. That ambition creates a need to measure the results and the progress due to the developments in AUTOMAIN. Table A indicates how each sub-objective should be measured. In general, this measurement always consists of:

- A measurement of the actual performance situation, either by actual measurements or by estimations of the actual numbers.
- Quantification of the effect of the improvements achieved by the WP by measuring, by estimating or by using the results of the demonstrator (WP6).
- Calculating an overall effect for the objective, basically using the formula[6]:

equation 1

$$Improvement = \frac{actual\ possession\ time - new\ possession\ time}{actual\ possession\ time} \cdot 100\%$$

or

equation 2

$$Improvement = \left(1 - \frac{new\ possession\ time}{actual\ possession\ time}\right) \cdot 100\%$$

Note that, in order to calculate the overall effect, the information is necessary in absolute figures, such as hours or minutes. Table A also indicates which WPs contribute to each objective and thus which WPs will have to provide the relevant information.

The summations of the above five sub objectives will confirm if the main objective of achieving 40**%** reduction of maintenance possession time has been achieved or not. Similarly, relevant WPs will work out the related KPIs/PIs and apply them to verify the results. The overall results (the top box in Figure 7) will be calculated by WP1 as part of task T1.3, using the data provided by the other WPs.

Table A; Specification of the validation methods for each AUTOMAIN objective.

Nr.	Objective	Measurement of impact by	WP
1	Adopting best-practices from other industries.	For each component allocated as possible measure: • Mapping of today's needed possession time for maintenance. • Mapping of expected time for maintenance when using the proposed improvement (a.o. through the lean approach). • Quantifying total required possession time when proposed improvements will be used. • Comparison of today's required possession time for maintenance vs. possession time for maintenance using proposed improvements. • **KPI_1 = (1 – possession time required for maintenance using innovation / actual required possession time for maintenance) x100%.**	2
2	Novel track inspection approaches.	For each activity allocated as possible measure (by WP 1& 2): • Mapping of today's required possession time for inspection. • Mapping which components can be measured in equal quality by in-service trains (the novel track inspection approach).	3

[6] The results of these formulas depend on the type of track they are applied to. The reduction of possession time on a heavily utilized track is much more difficult than on a lightly utilized track. In case this is a relevant issue, each WP has to consider the consequences and explain how this affects the results.

Nr.	Objective	Measurement of impact by	WP
		• Mapping of expected required time for track inspection when using the proposed improvement. • Quantifying the remaining amount of required possession time when in-service trains are used. • Comparison of today's required possession time for inspection versus inspection time when using in-service trains[7]. • **KPI_2 = (1 – possession time required for inspection using the novel approach/ actual required possession time for inspection) x100%** Remark: identify what is needed to reach the same level as today's quality when practicing the innovation.	
3	Adoption of innovative techniques for large scale maintenance.	For each component allocated as possible measure (by WP 1& 2): • Mapping of today's required possession time for large scale maintenance. • Mapping of expected required possession time for large scale maintenance when using the proposed innovative techniques. • Quantifying the amount of remaining required possession time when proposed improvements will be used. • Comparison of today's required possession time for large scale maintenance vs. time for large scale maintenance using the proposed improvements. • **KPI_3 = (1 – total possession time required for maintenance using innovative techniques/ actual required possession time for maintenance) x100%** Remark: identify what is necessary to reach the same level as today's quality when practicing the innovation.	4
4	Modular infrastructure design.	• Mapping of today's required possession time for installation, maintenance and inspection. • Mapping which components can be measured in equal quality by using modular and self inspecting components. • Quantifying the amount of remaining required possession time for installation, maintenance and inspection when modular	3, 4

[7] According to the actual insight of WP6, the in-service train used in AUTOMAIN may not reduce possession time to the desired level, as it does not completely replace regular inspection (trains). The big impact is the increase of measurement quality on lines. The additional measurements and improved quality lead to a better prognosis of required maintenance. The objectives mentioned here are based on the information in the DoW. In case the WP concludes that the objective is too ambitious, the WP itself shall explain the shift in potential gain and describe in what way the overall effects contribute to the AUTOMAIN objectives.

Nr.	Objective	Measurement of impact by	WP
		components are used. • Comparison of today's required possession time for installation, maintenance and inspection vs. required possession time for installation, maintenance and inspection using modular components. • **KPI_4 = (1 - possession time required after using modular elements/ actual required possession time) x100%** Remark: This should be exercised for inspection as well as for maintenance activities.	
5	Better planning and scheduling tool to optimise the programme.	• Inventory of annual claims for possessions (time) in combination of included components. • Mapping of today's required possession time for maintenance. • Mapping of expected required possession time when using the proposed improvement with the same amount of components to be maintained. • Comparison of today's required time for installation, maintenance and inspection vs. expected required possession time for installation, maintenance and inspection when components are planned and scheduled in an innovative way. • **KPI_5 = (1 – possession time needed when using innovative scheduling tool/ actual needed possession time) x100%.** Remark: This should be exercised for inspection as well as for maintenance activities.	5

2.5. References

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3. Evaluation framework.

3.1. Innovation evaluation criteria.

Within the AUTOMAIN project five key innovations are planned:

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

Innovation 2: Higher speed infrastructure inspection methods;

Innovation 3: Higher speed track maintenance methods;

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

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.

The project proposes five operating concepts, as shown in Figure 8:

1. Present situation – this is considered to be the current status quo of the rail, i.e. where the railway is ‘shut’ for a fixed time at night to allow inspection and maintenance to be carried out.
2. Maximised availability – this is considered to provide increased capacity by allowing more train paths (compared with operating concept 1) by reducing the amount of time that the railway needs to be shut at night. This can be achieved by optimising the maintenance tasks through: more efficient processes, better planning and use of time; elimination of unnecessary tasks; high-speed machinery; full automation of tasks (e.g. inspection).
3. Availability on demand – this is considered to allow maintenance to be carried out in short blocks when the railway is not in use; this may be at night or during under-utilised periods during the day. This would result in a railway that is not shut at night. In this way extra train paths would be created.
4. 24/7: Maintain between services – this is considered to allow inspections and maintenance to be carried out between trains in a normal operating timetable. Such an approach would significantly increase the number of train paths available.
5. 24/7: Maintenance-free (out of the scope of the AUTOMAIN project) – this is considered to be a railway where the need for inspection and maintenance time has been totally eliminated either through the improved design of the system or complete automation.

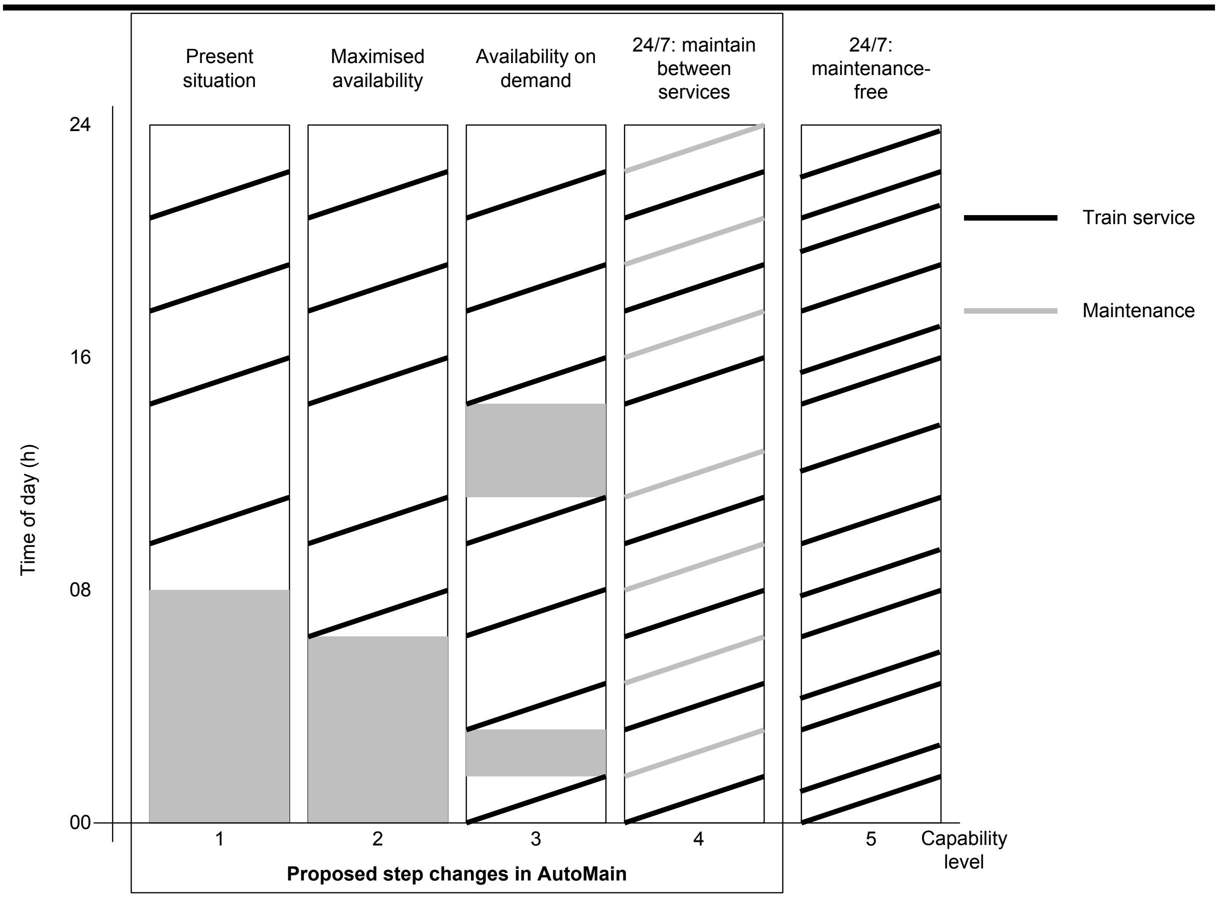


Figure 8; The five operating concepts considered in the AUTOMAIN project (equal to Figure 1).

It is important that each of the innovations in the project has an appropriate framework by which it can be evaluated at the end of the project. This evaluation framework should be composed of a set of criteria:

1. The contribution it has towards the appropriate proposed step change operating scenarios considered in the AUTOMAIN project (maximise availability; availability on demand; 24/7: maintain between services; 24/7 maintenance-free);
2. The capability requirements identified in D1.1 (see Appendix C);
3. The contribution towards the high level objectives of the project;
4. Measure of increased train paths.

Table B; Innovation aspects and evaluation criteria.

Innovation	Evaluation Criteria
1 **A new methodology for analysing and**	**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

Innovation	Evaluation Criteria
optimising maintenance processes by applying best practices from other industries.	demonstrate how the benchmark possession time for key maintenance tasks can be reduced by up to 50% (Objective 1). **iv. Current Technology Readiness Level[8]:** 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.
2 **Higher speed infrastructure inspection**	**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.
3 **Higher speed track maintenance.**	**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.
4 **Modular**	**i. Primary KPI:** KPI_4 = (1- possession time required after using modular elements/ actual required possession time) x100%

[8] Refer to “List of abbreviations and acronyms.” in this report for further explanation.

Innovation	Evaluation Criteria
infrastructure components and subsystems.	**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.
5 **The improvement of automatic maintenance scheduling and planning systems.**	**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:** Possession time for key maintenance tasks (e.g. tamping) to be reduced by 40%. This should be assessed through detailed analysis and DS1 and DS2.

3.2. Demonstration evaluation framework.

Two demonstration scenarios are planned in WP6 of the AUTOMAIN project:

DS1 – in-service track monitoring using a freight locomotive

DS2 – modular, self-inspecting switch

3.3. DS1: In-service track monitoring using a freight locomotive.

The aim of DS1 is to demonstrate a system that is able to automatically carry out inspection and analysis of track geometry from an in-service freight train. Such an innovation is particularly important on congested freight routes that are either today, or in the future, close to maximum capacity and operate 24 hours per day. Such levels of operation mean that it is difficult to gain access to the railway to carry out conventional inspection by humans, and it is even difficult to gain train paths to operate specialist measurement trains. There is therefore a requirement to carry out inspection from an in-service vehicle. Typically such routes operate across country borders.

3.3.1. Solution to be demonstrated.

DS1 has to answer the following question:

Is it possible, using the developed innovations from AUTOMAIN, to monitor the quality of the track from a freight-train in its normal in-service pattern?

The key challenges of the demonstration are therefore both to identify an appropriate, robust sensor system design and to develop automatic data analysis routines to extract key inspection information. The second challenge is particularly important due to the large quantity of data that will be acquired by such a system.

The monitoring system to be demonstrated in DS1 will provide track alignment and track defect information. These data will be displayed using a man-machine interface (MMI) that can be used for the presentation and analysis of all data types (for example, the MMI will also be used for DS2). For DS1 the output of the MMI will include:

- a maintenance needs assessment, based on the analysis of the track geometry data;
- an optimised maintenance date and plan.

Figure 10; Map of Route 2 – the 'Rheintalbahn'

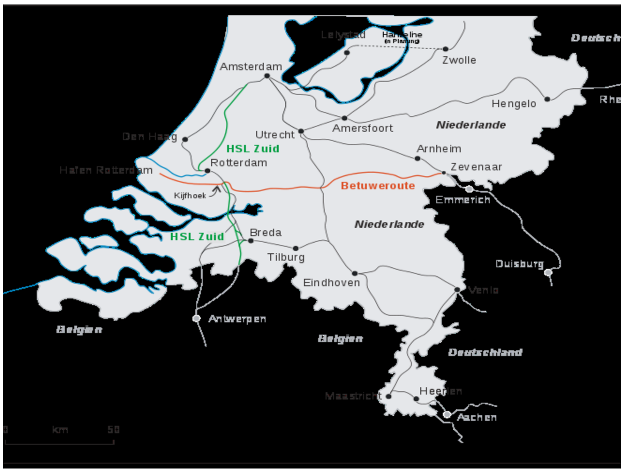


Figure 9; Map of Route 1 - the 'Betuweroute'.

3.3.2. Potential routes.

This will be demonstrated by Deutsche Bahn. To date Deutsche Bahn has identified three potential freight routes that are being considered in WP6 for DS1:

Route 1 – The Betuweroute (European Freight Route 1), which is a double track railway that runs between Rotterdam, Netherlands and Cologne, Germany (see Figure 9). The line is a dedicated freight route, which currently runs at high capacity and carries 78% of the freight train traffic between the Netherlands and the German border. Figure 9 shows a map of the route.

Route 2 – The Rheintalbahn, which is a double track railway running from Basel, Switzerland to Mannheim, Germany. The route is a mixed traffic line. Figure 10 shows a map of the route.

Route 3 – The route which runs from Bad Bentheim, Germany to Halsberg, Sweden (via Denmark and the Öresund Bridge). The route is a complex mixed traffic line where services interact with many existing passenger and freight services. Figure 11 shows a map of the route.

Each of the three routes needs specially equipped locomotives. Therefore the demonstration of the measurements cannot be carried out on all routes.

Figure 11; Map of Route 3 – the rail corridor between Scandinavia and Germany.

3.3.3. Relevant evaluation criteria for DS1.

The Table C below shows the evaluation criteria applicable for DS1.

Table C; Relevant innovation aspects and evaluation criteria for DS1 (contains a subset of Table B).

Innovation	Evaluation Criteria
1 **A new methodology for analysing and optimising maintenance processes by applying best practices from other industries.**	**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.

Innovation	Evaluation Criteria
2 **Higher speed infrastructure inspection**	**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.
5 **The improvement of automatic maintenance scheduling and planning systems.**	**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:** Possession time for key maintenance tasks (e.g. tamping) to be reduced by 40%. This should be assessed through detailed analysis and DS1 and DS2.

3.4. DS2 - Modular, self inspecting switch.

The aim of DS2 is to demonstrate the concept of the 'Self-Inspecting Switch', that is a switch which does not require any human inspection activities. The concept is to develop an automated sensing solution for all current mandatory switch inspection tasks (e.g. gauge measurement, frog wear, etc.). This work builds on some of the research carried out in the Innotrack project in this area. This approach moves forward from the existing condition monitoring work which has been implemented in a number of countries. Condition monitoring aims to detect and diagnose faults, whereas a self-inspecting switch will augment this capability by also eliminating the need for any human inspection techniques that are currently undertaken.

3.4.1. Solution to be demonstrated.

DS2 has to answer the following question:

Is it possible, using the developed innovations from AUTOMAIN, to have a switch installed that does not require any human inspection activities due to the installation of automated sensing systems?

The monitoring system to be demonstrated in DS2 will provide a complete check of all required components on a switch. These data will be displayed using the common man-machine interface (MMI) that will be used for the presentation and analysis of all data types (as for DS1). For DS2 the output of the MMI will include:

- a maintenance needs assessment, based on the analysis of the inspection data;
- an optimised maintenance date and plan.

3.4.2. Demonstration sites

DS2 will be shown in two settings:

1. Trackside – using the existing InnoTrack demonstrator in Malmö (Sweden);
2. Laboratory conditions – at either a Network Rail training school in the UK, or at the University of Birmingham Centre for Railway Research and Education (UK).

Furthermore, DS2 will consider the requirements for modular switch monitoring (i.e. the ability to 'plug 'n' play' switch monitoring systems by using a common interface).

The test site in Malmö will be used where the technology and processes developed can be proven within the timescales of the AUTOMAIN project to be safe for use on an operational railway. For processes and technology where the safety case is difficult to develop at this stage in the lifecycle, demonstration will take place on a switch in laboratory conditions (i.e. with no traffic).

Different standards for switch maintenance inspection exist that mandate the inspection of many different components of the switch, as shown in Figure 12. Depending on the criticality of the components, the inspection task includes at least one of the following checks:

- presence – check whether the component is missing;
- damage – check whether the component is visibly damaged in any way;
- measurements and gauge – check whether the component is within tolerance;
- integrity – check with the component is defect free and hence structurally sound.

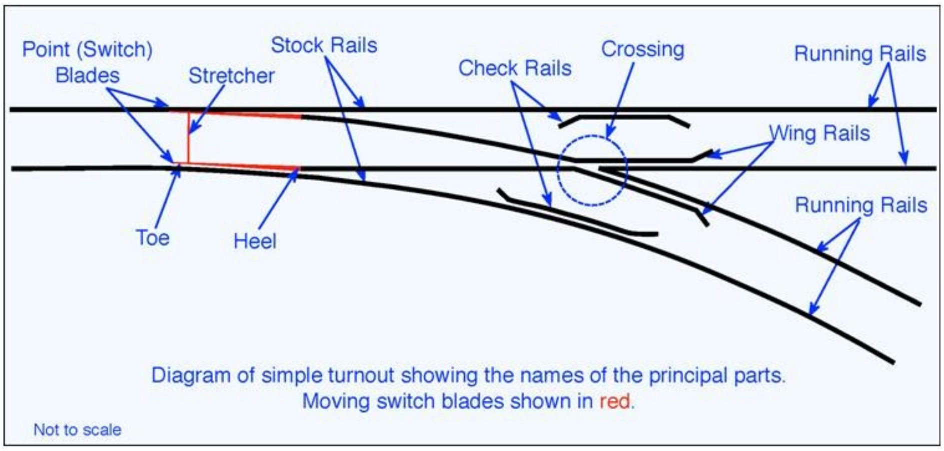


Figure 12; The many components of a switch which typically require inspection.

3.4.3. Relevant evaluation criteria for DS2.

Table D below shows the evaluation criteria applicable for DS2 (in order of importance).

Table D; Relevant innovation aspects and evaluation criteria for DS2 (contains a subset of Table B).

Innovation	Evaluation Criteria
1 **A new methodology for analysing and optimising maintenance processes by applying best practices from other industries.**	**i. Primary KPI:** KPI_1 = (1 – possession time required for maintenance using innovation / today's 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.
2 **Higher speed infrastructure inspection**	**i. Primary KPI:** KPI_2 = (1 – possession time required for inspection using the novel approach/ today's 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.
4 **Modular infrastructure components and subsystems.**	**i. Primary KPI:** KPI_4 = (1- possession time required after using modular elements/ today's 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

Innovation	Evaluation Criteria
	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.
5 **The improvement of automatic maintenance scheduling and planning systems.**	**i. Primary KPI:** KPI_5 = (1 – possession time needed when using innovative scheduling tool/ today's 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:** Possession time for key maintenance tasks (e.g. tamping) to be reduced by 40%. This should be assessed through detailed analysis and DS1 and DS2.

4. End-user requirements for the planning tool.

In this section, general end-user requirements are first presented in Subsection 4.1. The next four subsections introduce two scheduling and two planning problems to be addressed by the tool.

4.1. General end-user requirements.

The motivations of the tool are twofold:

- The automation of a process that, when made manually, needs a lot of time and expertise;
- The use of artificial intelligence and operational research techniques to assure an optimisation of the KPIs.

Summing up, the tool should be faster than human planners and find better solutions (compared with respect to the given quantitative objective functions to optimise and the given constraints).

WP5 objective is to create a tool able to find a feasible maintenance plan considering the specificities of each infrastructure. As a consequence, some flexibility in the definition of the constraints of the planning and scheduling models is required[9].

Maintenance activities have been identified and enumerated on the deliverables D2.1 and D2.2. It appears that activities could be classified according to their impact on network availability on the one hand, and to their costs on the other hand. Moreover, incompatibilities between operations as well as human and material resources have to be considered.

The feasible maintenance plan obtained by the tool has to respect all these constraints. Moreover, it has to minimise an objective function that expresses the cost and availability impact of each task. This objective function will be composed by a series of Key Performance Indicators (KPIs). These indicators will measure capacity and cost savings that could be reached thanks to the innovations proposed in WP3 and WP4.

Therefore the objective function should be a weighted summation of the KPIs like F_{obj} in equation 3, where KPI_i are the different KPIs to be maximised and w_i their associated weights.

$$F_{obj}(KPI) = \sum_i w_i KPI_i$$

equation 3

The weights therefore play a key role in the behaviour of the tool. They will have direct impact in the resulting schedule/plan, since they determine the prioritisation assigned to each KPI as objective of the optimisation. The assessment of adequate values will constitute a complex and decisive task, because KPIs may have different units (e.g. Euros and minutes). In the test scenarios predefined

[9] The development of commercial planning software that offers many modelling facilities to the end-user may require a work load of more than 100 person-years. Therefore, the objectives of WP5 will be far away from the level of a commercial tool. They will be explained in the problem solution document at the end of Q4 of the project.

values will lead to balanced schedules/plans in these particular scenarios. However, the user will be able to change them to represent his particular KPI prioritisation.

Although the objective function will be a sum of KPIs, in order not to lose generality, the user will be able to add other criteria to the objective function like, for instance, load balancing.

4.1.1. Collaborative planning and scheduling.

The interviews of D1.1 have shown that maintenance planners have to organise different kinds of schedules according to resources, space and time horizons. Clearly, the coordination between these schedules (for example schedules between different sub-networks) is crucial and complex when some resources are shared.

Collaborative planning is an attractive concept to achieve this coordination. In practice, a central platform could be set up to record not only the needs for maintenance and inspection but also the final or partial current schedules. Decision support functionalities are quite limited in the platform. They should consist of:

- Data visualisation
    - The GUI is the board that gives a global view of all the planning (and its conflicts)
    - We should be able to navigate and zoom
        - in time (from a one-month long time-bucket to a time-continuous scale),
        - In space (geographic area, sub-network, line, track segment),
        - on types of resources.
- Conflict detection
    - A rule-based engine could be used to manage all the constraints that are to be checked.
- Planning assessment
    - Multiple criteria (performance indicators) must be proposed.
    - A rule based engine can be useful to offer enough flexibility in formulating objective functions.

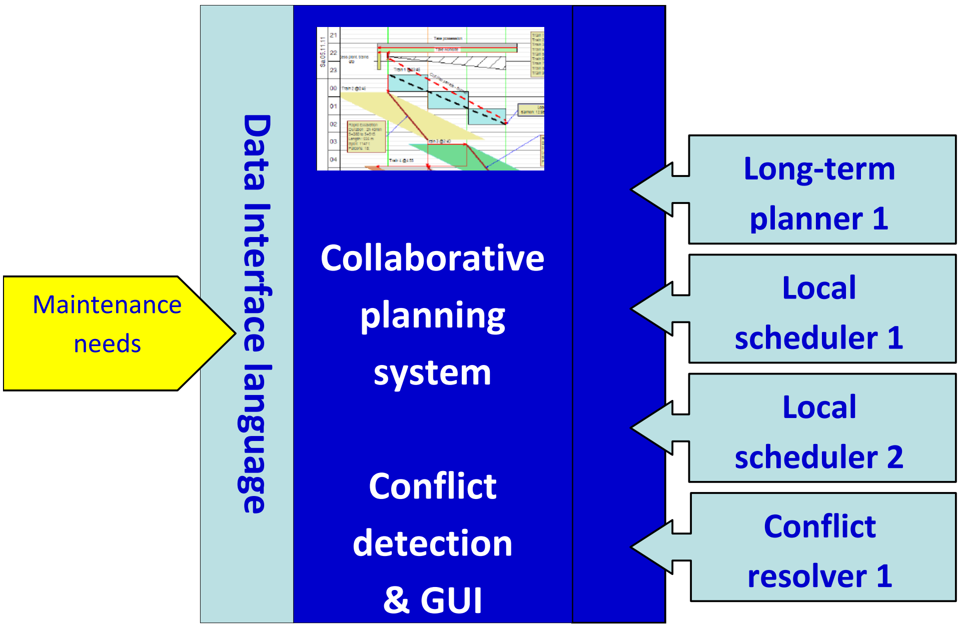


Figure 13; Collaborative planning system architecture.

Automated planning requires optimisation techniques that are far more complex to implement. Therefore, automated planning functionalities could be designed as external extensions (or plug-ins). A proposed architecture is shown in Figure 13. An interface is necessary so that each extension can read the required data and can propose tentative partial schedules to the collaborative planning system.

The planning and scheduling problems presented in Sections 4.2 to 4.5 are typical problems to be solved by these extensions. Thus, different modules could be developed for:

- Minimising the length of a track possession for a complex maintenance project;
- Minimising the amount of maintenance activities in one project;
- Load balancing to improve the robustness of the schedule;
- Optimising the use of critical maintenance resources;
- Rescheduling to decrease the number of constraint violations.

The use of the collaborative planning system should help to converge to a feasible timetable schedule (see Figure 14). Indeed, the planning process must:

- identify the maintenance operations that are necessary (in order to avoid over-maintenance);
- combine as many maintenance operations as possible (in order to minimise the track possession);
- take into account the track possession constraints;
- take into account the resource constraints.

Figure 14 illustrates how the successive solving of these four issues can lead to a feasible maintenance schedule. In a collaborative system, it should be possible to address the problem in any order and to re-address any of the problems as many times as necessary.

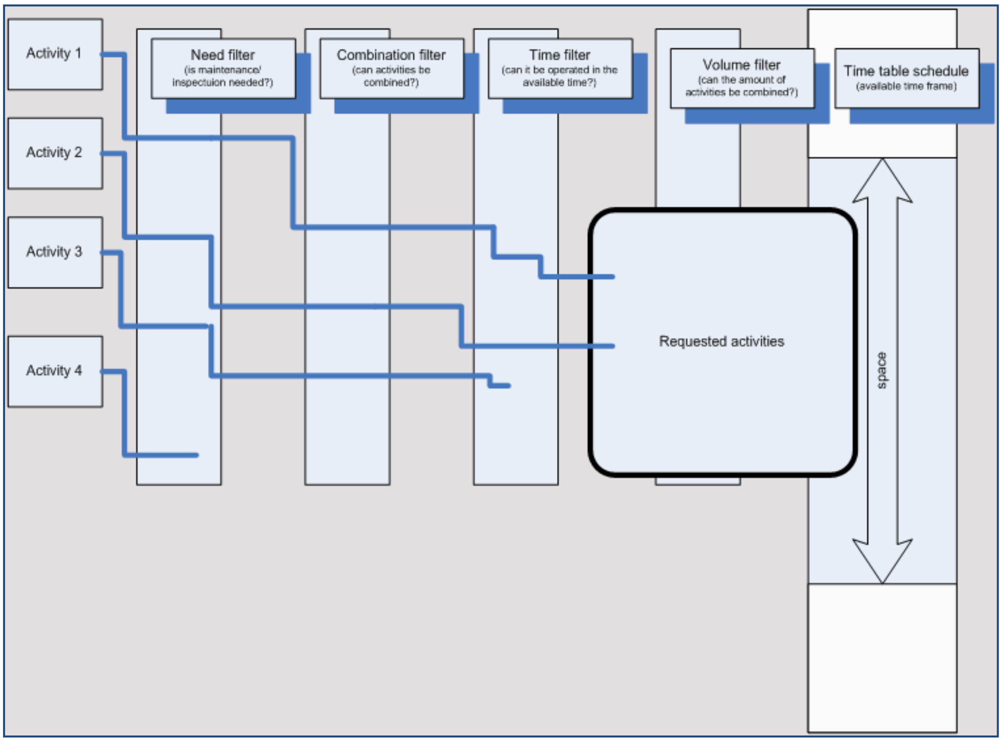


Figure 14; Convergence to a feasible timetable schedule.

In the context of AUTOMAIN, the budget of WP5 is limited. The development of a complete collaborative planning system is clearly out of the scope of the project and is not in the DoW.

4.1.2. User interface.

Beyond the scope of WP5, a powerful Graphical User Interface (GUI) is very important for any modern computer tool. The GUI of the planning tool is indeed the board that gives a global view of all the planning and the constraint violations that have not yet been solved. Some of the required features are listed in the previous section. They mean that the end-user should be able to easily navigate in the schedules and have views on performance indicators and possible problems (constraint violations). Zoom tools should help to have either large scale reports or a detailed view of the scheduling of a selected project.

User interface are also devoted to help the planner to test different schedules and to change a current schedule or plan. In most cases, drag-and-drop features are required by the end-user to move an operation from one resource to another or to change its duration or its start time. Form windows are also useful when a sufficient accuracy cannot be obtained through mouse moves.

In the previous section, it was stated that conflicts and performance indicators should be defined using a rule-management system so that the end user can define its own rules and indicators. End-users usually require that the definition of the rules be expressive and easy to understand (as close to natural language as possible). In business rules management systems (BRMS), some domain specific language can be defined. The rules can be edited in text files, office documents or in dedicated graphical interfaces.

GUI objectives for WP5: However, as indicated in the DoW, the tool delivered in D5.2 will have a simple GUI. Since it will only be a demonstration tool, the GUI development should not demand huge efforts. Its objective should be only the visualisation of the input data and the results. Edition of data input through advanced dedicated graphical interfaces is also out of the scope of WP5. In the WP5 planning tool, data will be read from external data files or a data base. However, for demonstration purposes, these input data should only be editable through an external tool such as a spreadsheet.

4.1.3. Scenarios.

Deliverables D1.1 and D2.1 show that maintenance activities are planned either 1 to 3 years or 1 to 3 months in advance. Activities could even be adjusted 1 day before execution. This variety of time scales implies the need to adapt the tool. Indeed, the underlying optimisation problem is very different, depending on whether one or another time scale is considered.

The decomposition of the whole problem into planning and scheduling sub-problems (see definitions of *planning* and *scheduling* in the glossary in Appendix B) is necessary in order to limit the combinatorial explosion that makes scheduling problems intractable, enhancing the possibility of developing and applying efficient search algorithms. Table E indicates the approximate size of the problem to consider. Clearly, the sizes and the time horizon can vary between the different European countries. Moreover, if the size of the problems has a strong impact on the computation times, other parameters such as the complexity of the constraints, may also impact the computation times. Therefore, Table E is only indicative.

Table E; Approximate indication of the size of the problem to consider.

	Large scale	Middle scale	Small scale
Max. Time horizon	1 to 3 years	1 to 12 months	1 day
Time Resolution	1 month or 1 week	1 day	1 minute
Max. Network size	National network	100-1000 km	1 km
Max. Calculation Time	1 h for the most complex cases A few seconds in some specific cases (see §4.2).	30 min	15 min

In practice, the boundaries between space scales and time horizon are not so strong and may depend on the IMs and the resources to be planned. In the following table, four problems are proposed that are the most relevant from the results of the questionnaires in D1.1 and the experience of IM partners.

Table F; The size and time indication of the proposed problems.

Problem:	P1	P2	P3	P4
Max. Time horizon	1 day	1 day / 6 hours	1 to 3 years	Several days or months
Time resolution	1 minute	1 minute	1 day or 1 week	1 day
Max. Network size	10 to 100 km	1 km	National network	National network
Max. Calculation Time	1h for the most complex cases A few seconds in some specific cases (see 4.2)	1 h	1h	5-15 minutes

All these problems should be mathematically formulated. Then the planning algorithms will determine the values of some decision variables. These variables could be the start and end times of the track possession time intervals and the time of the paths at the nodes of the networks. The mathematical model will also include a list of constraints that must be satisfied by the solutions that will be generated by the algorithms.

4.2. Time window insertion (problem 1).

The time window insertion problem (TWIP) is a short-term scheduling problem, aiming to set a theoretical schedule for some track possession and/or inspection or maintenance train paths on a given day. Here, time window means a space-time use of the track that is either a track possession for work or a train path for inspection or logistics trains. Therefore, the temporal horizon of the problem is typically 24 hours (even less than 24 hours if the time period of the day when the operations must be placed is known).

The maximum computation time allowed to solve the problem is one hour, but it would be preferable to have a good solution in the first minutes of calculation. As discussed in Section 4.4, instances of TWIP could be solved in a sub-routine in order to solve a more global planning problem. Clearly, this can only be done if the computation time is no more than a couple of seconds.

The goal of TWIP is to insert in an automatic way all the windows and paths in between the commercial trains already set in the schedule. Several criteria can then be formulated:

- Minimise the cost
    - A cost function must be given in order to assess the cost of a time window according to its start time.
- Minimise the duration
    - The duration is the time span between the start time of the earliest time window (or maintenance train path) and the completion of the latest one.
    - For example, if one train path is to be inserted, this objective function will minimise the total stopping time of the train.
- Minimise the disturbances on the business service
    - If it is not possible to place the operations without modifying the business service, a degraded mode can be considered, with the possibility to delay, advance or remove trains.
    - Penalties for early, late and removed trains must be given in input.

TWIP is related to capability requirements CR09, CR10, CR11, and CR12.

4.3. Worksite scheduling (problem 2).

The WorkSite Scheduling Problem (WSSP) addresses the issue of scheduling the maintenance interventions to be processed within a track possession period. The time horizon is typically the duration of the possession time window. The accurate list of elementary interventions is required as input data in order to know exactly how maintenance is processed. Each elementary intervention will be represented by a time window corresponding to its time and space extension.

Compatibility constraints will be defined to model whether or not two interventions may overlap. Each intervention also requires some resources; the availability of these resources also constrains the schedule.

The goal is to minimise the size of the working time windows by rescheduling the elementary tasks composing the complete possession. The size of the problem is around 15 to 20 elementary operations. Formally, the objective criteria to optimise could be as follows.

- Minimise the duration (time span between the earliest operation and the latest one). For example, if one train path is to be inserted, this objective function will minimise the total stopping time of the train).
- Minimise the total cost.

This problem requires very accurate data on behalf of both infrastructure manager and maintenance providers. In practice, building efficient and accurate models is a very long and collaborative work.

Related capability requirements:

- CR07;
- CR10 could be considered in this problem if logistics trains are entered as an elementary maintenance operation. However, due to computation complexity, these train paths must be short (from the nearest depot to the work site).

4.4. Long term planning (problem 3).

The goal of the track maintenance problems is to determine, in a time horizon of one year up to three years, which maintenance (or inspection) operations are to be processed on which track segment and in which time period (week or month). The issue of combining work is also addressed. The objective is to minimise track possession time and cost over the whole network managed by the IM. Typically the time horizon is divided into time buckets whose length is usually a week or a month. The railway network is partitioned into track segments but it can also be assumed that the network is continuous between two nodes and an operation is located between two points on the track.

For example, the following chart displays a planning for tamping operations to be scheduled on a track segment of several kilometres (*x*-axis). The time horizon is 2 years (*y*-axis) that is divided into 24 time buckets, each corresponding to one month. A cell is coloured when a maintenance operation is planed for the piece of track in the corresponding month.

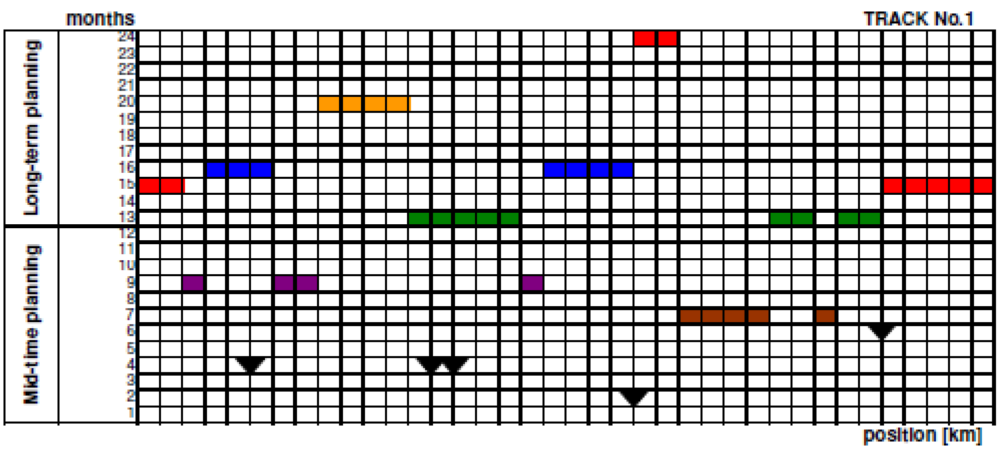


Figure 15; Mid and long term planning.

The time horizon of the long term planning problem (LTPP) is too large to deal with all the commercial train paths. By contrast, we assume that, in each time bucket, time intervals where track possessions are possible are known or will be computed later solving the scheduling problems previously introduced. In other words, we have a macroscopic description of the maximum capacity available for maintenance works. Similarly, we assume that logistic train paths for maintenance or inspection machines are given in input or can be computed later. Another important feature of the model is to propose an efficient description of the possible combinations of maintenance operations.

The mathematical function shall

- Minimise the track possession for inspection, maintenance and moves of machines;
- Minimise the total cost;
- Maximise the use of maintenance machines;
- Balance the work load between pre-determined sub-networks.

The allowed computation time should be at most one hour.
Related capability requirements:

- CR09, CR14;
- CR31 is related to multi-resource planning. However, the problem does not directly address the prognostic on the behaviour of the infrastructure.

4.5. Dynamic planning (problem 4).

A variant of this problem consists of adapting a given mid-term planning in order to insert new maintenance tasks that appear after inspection. The current planning is given in input; it is to be adapted (some planned preventive maintenance operations may be postponed). The proposed solution must stay operationally applicable. Therefore, the microscopic scheduling constraints must be satisfied, at least the ones known with respect to the time horizon. The computed solution must:

- Minimise the impact of the insertion on the initial planning;
- Minimise the cost increase caused by the adaptation.

Dynamic planning (DynPP) must be quite fast so that the planning changes can be applied in an operational context. Therefore, computational times should not exceed 10 minutes.
Related CR :

- CR09;
- CR12 is also partially addressed by the dynamic planning problem if we consider that maintenance can be processed within several days.

4.6. Overview.

In this section we provide an overview on the relationship between the planning and scheduling problems posed in sections 4.2 to 4.5.

- the end-user requirements enunciated in section 4.1.
- the capability requirements presented in Appendix A.

4.6.1 End-user requirements

Table G shows qualitatively which end-user requirements are related to which planning/scheduling problem. Next a more detailed description of these relationships is given.

- 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.
- 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.
- Planning assessment: Only LTPP and DynPP will be planning tools, i.e. they assess optimised maintenance plans.
- Scheduling assessment: only TWIP and WSSP are scheduling problems, i.e. they assess optimised schedules.
- 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.
- 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.
- 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 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.
- Over-maintenance avoidance: as stated in 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.
- 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.
- 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.

Table G; Relation between end-user requirements and planning problems. An empty cell means no relation, "+" a moderate and "++" a strong relationship.

	TWIP	WSSP	LTPP	DynPP
Data visualization	++	++	+	+
Conflict detection	++	++	++	++
Planning assessment			++	++
Scheduling assessment	++	++		
Track possession minimization	++	++	++	++
Work load balancing			++	+
Critical resource use optimisation			++	
Rescheduling to decrease constraint violations	+	++		++
Over-maintenance avoidance			+	
Operations combination		++	++	++
Consider track possession and resources constraints	++	+	+	++

4.6.2 Capability Requirements (CRs)

Table H shows qualitatively which CRs are related to which planning/scheduling problem. Next a more detailed description of these relationships is given:

- CR07: this deals with problem 2. The possibility of bundling work will be an input data for problem 2; the tool will not determine which operation can be done with another. Nevertheless, the tool will be able to show the impact of the packaging on the planning.
- CR09: See comments about the GUI in section 4.1.2.
- CR 14: the scheduling frequencies are an input of problem 4.
- CR 31:
  - WP5 does not address the problem of generating the maintenance laws that determines the maintenance operations from inspection measurements. The planning tool can however propose to provide temporal constraints and cost (objective) functions that both reflect the impact of the laws. For example, early maintenance is penalised (due to over-maintenance) and late maintenance is penalised to increased risk. For computational efficiency, operational research models usually assume linear cost functions. In WP5, the use of non-linear (but simple) functions may however be investigated.
  - WP5 does not address the problem of analysing raw measurement data.

Table H; Relation between CRs and planning problems. An empty cell means no relation, "+" a moderate and "++" a strong relationship.

		TWIP	WSSP	LTPP	DynPP
CR07	Package?? Bundling? work		++	++	+
CR09	Track condition on a map	+		+	+
CR10	Access work site rapidly	++	+		
CR11	Egress work site rapidly	++	+		
CR12	Carry out reactive maintenance	+			++
CR14	Low frequencies for maintenance			++	+
CR31	Multi-aspect optimisation		+	++	++

5. The applicability of the developed requirements and evaluation criteria.

5.1. Formal approval.

The results of task T1.2, as described in this report, have been the subject of discussions in the AUTOMAIN project management team several times, especially during the telephone conferences on January 23 and 27 2012, when all other WP-leaders could bring in their opinions. Eventually, during the call on January 27, all participants agreed with the draft version and the performance indicator as they are defined in Table A.

5.2. Further process.

The results of this task T1.2 are a starting point for further work in the WPs. Together with the requirements as described in D1.1, the indicators, requirements and evaluation criteria shall be the main reference for the work in the work packages.

In each relevant WP (mainly WP2[10],3,4,5 and 6) the following phases will have to be organised:

1. An overview of the relevant CRs, PIs and other requirements (based on D1.1 and D1.2) has to be made available.
2. A brief investigation has to be done in order to find out how to meet these objectives. Part of the investigation deals with the necessary information (sources, reliability, accuracy) and a more detailed definition of PIs (or even defining other, more specific PIs). In case the WP concludes that the available budgets do not allow it to meet the objectives, this issue shall be discussed in an early phase and shared with the project manager.
3. The required activities to gather the relevant information have to be incorporated in the WP's working plan.
4. The final report of the WP has to contain a chapter dealing with the results in terms of the information and PIs defined in D1.1 and D1.2. This chapter contains all information for task T1.3 to evaluate the result of the WP as well as the overall results of AUTOMAIN.

Under the responsibility of WP1, an overall evaluation of the project will be made (task T1.3). This evaluation merely shows if AUTOMAIN has met the original overall objective of reducing the required possession time for maintenance by 40% (the top box in Figure 7). It will be published in month 36 of AUTOMAIN (February 2014).

[10] Concerning the work in WP2 the indicated order of activities will probably differ, as the final report D2.2 has already been written at the moment report D1.2 is issued officially.

6. Overall conclusions.

6.1. General conclusions.

As a result of the work done in task T1.2 within work package 1, the evaluation of the future results of AUTOMAIN has been defined more precisely. The following ways of evaluation have been set:

- For each objective of AUTOMAIN a quantitative performance indicator has been defined. At the same time, for each objective it has been indicated which WP contributes to that specific result.
- For all intended innovations ways of evaluation have been set, eventually combined in an evaluation matrix.
- For each demonstrator (WP6) it has been indicated what part of the solution has to be demonstrated.
- For the planning and scheduling tool more specific requirements have been defined.

These instruments will help the WPs to define their derived objectives and the way to verify them. Altogether these instruments will also facilitate the overall evaluation of the results of AUTOMAIN at the end of the project.

6.2. Tabular overview.

In Table I below all mentioned PIs, work packages and innovations are shown along with how they are linked.

Table I; PIs, WPs and innovations and their relations.

PIs	Objectives					Work packages						Innovations				
	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

PIs	**Objectives**					**Work packages**						**Innovations**				
	O1	O2	O3	O4	O5	WP2	WP3	WP4	WP5	WP6-1	WP6-2	1	2	3	4	5
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

A. Appendix: Capability requirements elicited in D1.1

In report D1.1 functional and capability requirements have been defined. This table lists them again.

I.D.	Capability Requirements (CRs)
Capability requirements: 2026 –Time horizon The following capability requirements were identified as being important to railway maintenance in 2026:	
CR01	To be able to collect data using automated methods.
CR02	To be able to transmit data rapidly.
CR03	To be able to process and disclose data within 24 hours.
CR04	To be able to collect and measure data at line speed (140 kph).
CR05	To be able to reduce the necessary time for activities (TTR/TTM). To be able to renew track components easily.
CR06	To be able to predict trends in track degradation.
CR07	To be able to package/combine work.
CR08	To be able to record loads applied to the track.
CR09	To be able to reference all track condition data/faults against a network map.
CR10	To be able to access work sites rapidly (planning)
CR11	To be able to egress work sites and handover to operations rapidly (planning)
CR12	To be able to carry out reactive maintenance rapidly
CR13	To be able to plan on the basis of very low levels of reactive maintenance.
CR14	To be able to achieve very low frequencies for planned maintenance.
CR15	To be able to have very low track renewal frequency.
Capability requirements 2036–Time horizon In addition to the requirements for 2026, the following capability requirements were identified as being important to railway maintenance in 2036:	
CR20	ICT-supported access regimes and safety measurements.
CR21	To be able to have real-time data processing.
CR22	To be able to have instant access to processed data results.
CR23	To be able to have new switch and crossing designs with far fewer discontinuities (more like plain line).
Capability requirements 2051–Time horizon In addition to the requirements for 2026 and 2036, the following capability requirements were identified as being important to railway maintenance in 2050:	
CR30	To be able to embed knowledge and decision rules in the design of objects and their control systems.
CR31	To be able to optimise scheduled activities automatically on multiple aspects based on measurements, known behaviour and trend analysis.

B. Appendix: Glossary of planning terminology.

Preliminary discussions during the kick-off meeting have shown that many terms can be understood in different ways by the different stakeholders of AUTOMAIN. Therefore, this section is devoted to the definition of these reference terms in the context of AUTOMAIN WP5.

Time horizon:

- Completion time of the last task in the plan or in the schedule.
- Example: The time horizon of AUTOMAIN is February 2014.

Time bucket:

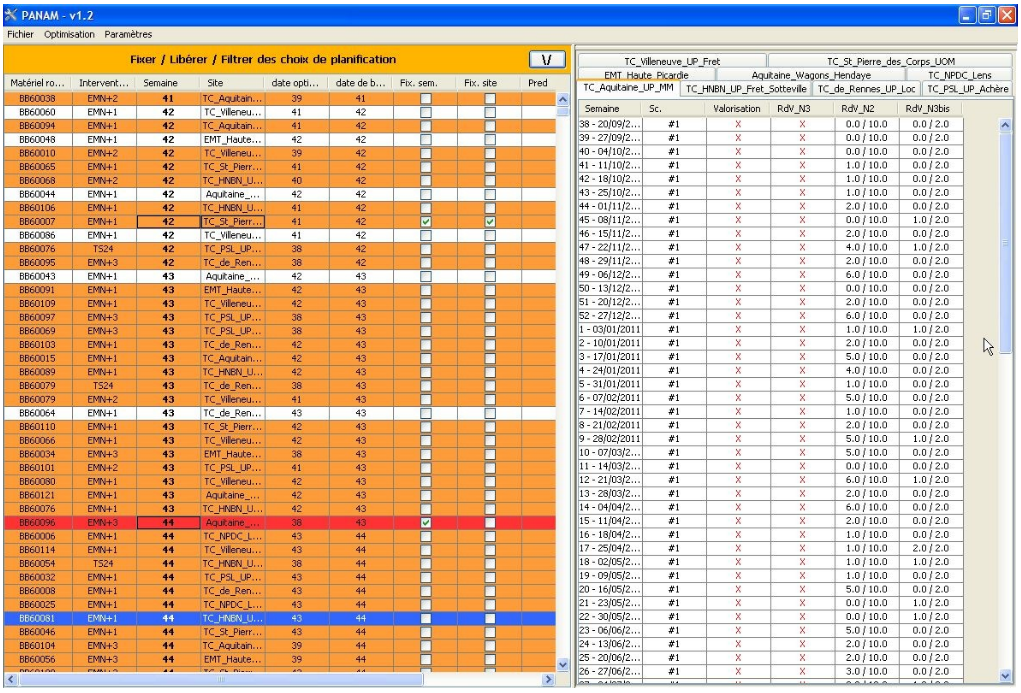
- Short timeframe in which a set of operations are to be processed.
- Typical time buckets are one week or one month.
- Sometimes an operation must be processed over two adjacent time buckets but the duration of an operation is usually shorter than the duration of the time bucket.

Resource:

- Anything that is required to perform a task
    - track
    - human workers
    - work trains
    - machines
- Critical resources are the most constraining resources when building the schedule. In practice, they are the rarest and the most expensive ones.
- Resource must be shared between all the maintenance tasks and with other activities. For example, the track is shared with commercial trains.

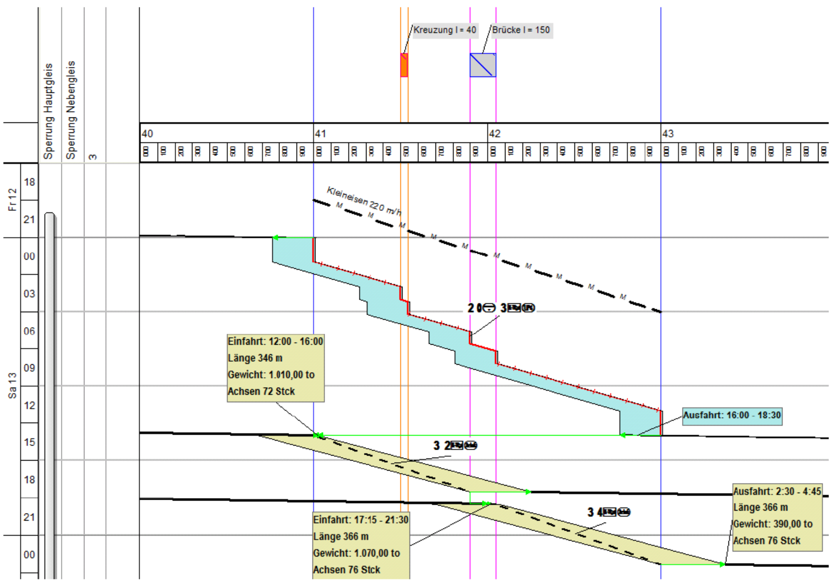
Planning → Automatic planning:

- Algorithm to derive a feasible optimised planning from a set of constraints and an objective function (KPI).
- Input
    - Implicit definition of tasks, some tasks can be performed in different ways (multi-mode)
    - Approximate, macroscopic definition of the resources
- Output
    - How each task is processed
    - Tasks assigned to « large » time buckets (one month, one week) subject to resource constraints
- In planning problems, most tasks are shorter than the length of the time bucket. The following figure displays a planning solution. In the left part of the window, operations to be planned are listed. They are all assigned to one week when they are to be scheduled. In the right part of the window, each line corresponds to a week and columns show workload for different resources.



Scheduling → Automatic scheduling:

- Algorithm to derive a feasible optimised planning from a set of constraints and an objective function (KPI).
- Input
    - Explicit list of tasks to be processed
    - Detailed definition of the resources
- Output
    - Detailed assignment of tasks to resources
    - Tasks scheduled at a given minute
- In a scheduling problem, tasks typically last several minutes, which is longer than the time precision. Schedules are generally displayed as space-time graphs or as Gantt charts.



Model:

- Set of constraints that must be satisfied.
- Objective function (derived from the performance indicators).
- Variables and literal parameters; no numerical data.

Scenario = instance = problem:

- Models with all data and parameters instantiated by numerical values.
- WP2 should define some scenarios. Some precisions will probably have to be brought.

Tool:

- In the context of WP5, the tool to be developed is a non-operational prototype. Indeed, its purpose is to prove the concept of automated planning in the context of track maintenance.
- More precisely, the output of the tool will be quite simple:
    - Data files / Tables
    - Basic graphical figure, typically a time-space diagram

C. Appendix: List of figures and tables.

Figures: **Page**

Tables: