Milestone MS6

Demonstrator concept and

first prototype for improved

timetable planning

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Report contributors		
Name	Beneficiary	Details of contribution
Martin Joborn	RISE	Editor
Sara Gestrelius	RISE	
Martin Kjellin	RISE	
Magnus Wahlborg	TrV	
Anders Peterson	LiU	
Carl Henrik Häll	LiU	
Christiane Schmidt	LiU	
Behzad Kordnejad	KTH	
Ingrid Johansson	KTH	
Jennifer Warg	KTH	

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Executive Summary

This document outlines the demonstrator that will be developed in Fr8Rail II WP3. One important objective of the document is to make all involved parties agree on the specification and the time plan for the development. The demonstrator will consist of two parts, an "intelligent planning module" and a "simulation module". The intelligent planning module is aimed at modifying existing timetables in order to incorporate late changes like change arrival time of a train or update a train's speed profile. The simulation module is aimed at analysing and visualizing the robustness of a railway timetable. The demonstrator will be applied on a test case based on the Swedish Southern Mainline.

Abbreviations and acronyms

Abbreviation / Acronyms	Description
IM	Infrastructure Manager
TD	Technical Demonstrator (concept used in Shift2Rail)

1 Background

This document constitutes the Milestone MS6 *Demonstrator concept and first prototype for improved timetable planning* of the FR8RAIL II project, Work package WP3 *Real-time network management and improved methods for timetable planning*, Task T3.1 *Demonstrator development for improved timetable planning*. More specifically, the document concludes the result of subtask T3.1.2 *To define demonstrator concept and a first prototype.* In the Grant Agreement, this subtask is described as:

To define research prototype platform with following aspects:

- *Timetable planning (long-term, short-term, ad-hoc) and operational feasibility*

- *Limited set of operational constraints communicated between RU, IM, YM and MC.*

- *Calculated relevant KPI*

- *Input and output in standardized formats (RailML)*

- *Source for timetable and (relevant) infrastructure data*

- *Modular based with plug-in possibilities for add-on functionality*

- *Graphical representation of timetables*

- *Open-source*

- *Fits to "integration layer", specified in Shift2Rail*

To write a specification of the demonstrator and develop a first prototype. Defining test scenarios for verification in Task 3.1.6.

Thus, one aim of the task is to develop a demonstrator for timetable planning. The objective of this milestone is to outline and specify the demonstrator in order to:

- Set the right expectations of the demonstrator
- Set a basis for collaboration between the project parties
- Describe the progress of the demonstrator work and its current status

The description of the demonstrator includes:

- Scope and limitations of demonstrator
- Functionality
- Data types and data format
- Data used for demonstrated scenario
- Typical usage scenario

- Proposed IT-architecture

At current date, there exists a prototype of the demonstrator. The demonstrator builds upon work in previous Shift2Rail projects, and this milestone also describes how the current demonstrator enhances previous demonstrator work. However, this document does not describe the current status of the demonstrator – that is better demonstrated.

The milestone does not include any implementation details or detailed algorithmic descriptions, even though e.g. some algorithms are outlined.

1.1 Demonstrators in previous Shift2Rail projects

In this section we summarize some demonstrator work that has been performed in other related Shift2Rail projects. The demonstrator described in this document will to great extent build upon the demonstrators from other projects.

ARCC

The ARCC project ran between 2016 and 2019 and was focussed on (WP1) transporting and delivering freight transport via automated trains, (WP2) developing automated support processes that are carried out at the system's nodes and (WP3) improving yard and railway network management through advanced timetable planning. In WP2, yard-line interaction was investigated, and a specification for a real-time yard management tool was developed [ARCC 2017, 2018/1, 2018/3, 2019]. In WP3, the state of the art and research gap for advanced timetable planning was investigated and initial development of a single train insertion algorithm was carried out [ARCC, 2018/2]. This algorithm was further developed in FR8HUB WP3 [FR8HUB, 2019].

While the main focus of the ARCC project was yard-line interaction and the main focus of FR8RAIL II is line planning, both projects consider planning platforms for connecting more than one planning module (and in ARCC – more than one planning process). Further, the methods developed in FR8RAIL II are important for the overall future scenario envisioned in ARCC where the line manager should be able to quickly replan a train path to better cope with disturbances and deviations. In addition, the yard-line cooperative planning platform ideas introduced in ARCC will be further developed in FR8RAIL III and will provide an extended prototype environment for the FR8RAIL II demonstrator. Thus, the methods and demonstrators developed in FR8RAIL II and FR8RAIL III complement each other and build on the results of ARCC and other previous projects.

IMPACT-2

In several previous projects, RISE has developed the timetable optimization software M2. M2 can use different objective functions to optimize existing timetables, add trains to timetables, or create timetables from applications made by train operators. Furthermore, M2 can present

optimization results in the shape of graphical timetables. In the IMPACT-2 project, RISE continues the development of M2, with the goal to turn it into a research platform. This means that it will be easier for researchers outside RISE to use M2 in their own research, to exchange data between M2 and other systems, and possibly to extend the program. The graphical user interface of the program will be improved, so that users can easily choose which data to use and set different parameters for the optimization process.

In the demonstrator described in this document, M2 will be responsible for data handling, user interaction and visualization. This means that M2 will manage a database of timetable data, provide a user interface where the problems to be solved are defined, produce a conflict-regulated timetable that will be the basis for the modifications to be made by the demonstrator, and visualize the results of modifications and simulations as graphical timetables. The role of M2 in the demonstrator will be further described in Section 2.2.

PLASA and PLASA-2

The Shift2Rail project PLASA WP1 "Smart Planning and Safety for a safer and more robust European railway sector" aimed at improving the state-of-the-art for tactical simulation. Hence, the planning horizon of the Smart Planning use cases was reduced significantly. The final goal of Smart Planning approaches was to simulate railway traffic on an operational level, thus aiming to investigate current technological limits in terms of computation time and manual effort required.
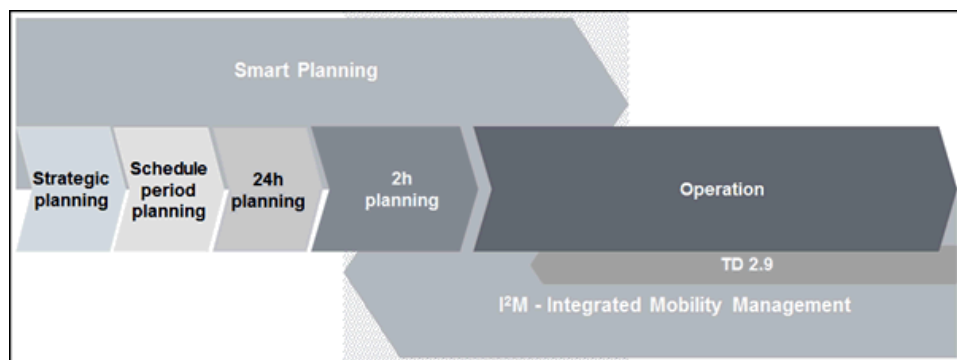

Figure 1: Planning horizons covered by PLASA/Smart Planning.

Within the framework of the project three separate deliverables were produced: D1.1 – Quality Plan, D2.1 – Summary of state-of-the-art in simulation and D3.1 – Summary of analysed disruption types. The first two reports are public and the final report is confidential. D1.1 dealt with internal project management and quality control, and D2.1 had the objective to analyse railway stakeholders' planning activities in order to clearly define the requirements, potential impact, and scope of innovation of Smart Planning methods and to give an overview of the

current state-of-the-art in simulation for railway traffic planning, both microscopic and macroscopic techniques for railway simulation are covered. Microscopic and macroscopic methods are commonly used for strategic purposes considering the annual timetable planning, through either detailed local computations or respectively network optimization. Microscopic methods consider local computations such as calculating running times and blocking times for a given infrastructure and signalling configuration, as well as for conflict detection and computing capacity consumption.

In order to be able to estimate the quality of a planning result, it is necessary to simulate the timetable in real-life conditions. Thus, PLASA aimed to create a high-quality stochastic disruption model that was able to reproduce real-life disruption patterns, but which is also editable by the user (e.g. to simulate the effect of reducing certain infrastructure disruptions). The model and the corresponding results are further elaborated in with a summary of analysed disruption types in the study of [Plasa D3.1, 2018].

The research of PLASA was validated with a proof of concept by implementing a software prototype (later named PRISM).
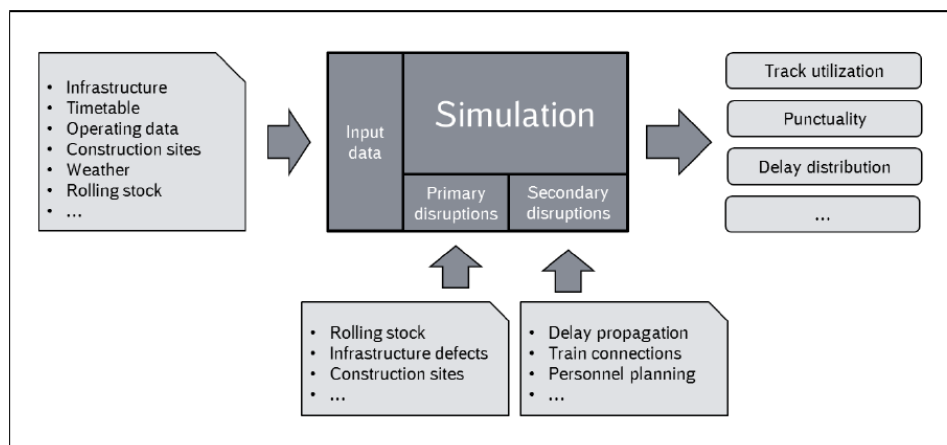

Figure 2: First draft of the PLASA software prototype PRISM.

The concept of the different modules of PRISM (data input, disruption model, level of detail of the simulation, etc.) was implemented with a clear distinction between data interface and internal computation. Thus, future enhancements (e.g. results of PLASA-2) could be integrated into the simulation concept without great efforts. Such a modular structure also enabled future changes for the regarded level of detail. Here, more microscopic aspects can be integrated where needed and a more stochastic, macroscopic relaxation can be used, where the complexity of the model is in conflict with the runtime goals. Future improvements could easily replace given modules, e.g. by enhancing the given disruption models or by implementing improved

dispatching rules. The output of the simulation will contain certain quality measures e.g. track utilization, punctuality, delay distribution, etc. [PLASA D2.1, 2017].

Valuable inputs to FR8RAIL II WP3 from PLASA can be summarized accordingly:

- A comprehensive overview of the state of the art in timetable planning
- An overview of the planning tools used in practice by railway stakeholders
- A clear vision of the gap in current planning capabilities that future work in the project PLASA-2 will attempt to fill
- First draft of the software prototype PRISM
- Simulating the effect of reducing certain infrastructure disruptions.
- The intention is to use PRISM in this demonstrator to evaluate the timetables.

The macroscopic railway traffic simulation tool PRISM is under further development in the currently ongoing project PLASA-2.

FR8HUB WP3

The aim of work package 3 (WP3) of the FR8HUB project was to develop methods for yard and network management, with a special focus on evaluating the effects on line capacity. Within the work package, two demonstrators (modules) for timetable replanning were developed – one for tactical planning and one for use in an operational setting. The results from the module for tactical planning can be shown in a timetable viewer, which was also developed in the project (see Figure 3). The module for tactical planning was developed at KTH and builds on previous results from [Högdahl et al., 2017], while the operational planning module was developed by Linköping University (LiU) and builds on previous results from [Ljunggren et al., 2018]. The timetable viewer was developed by Indra.
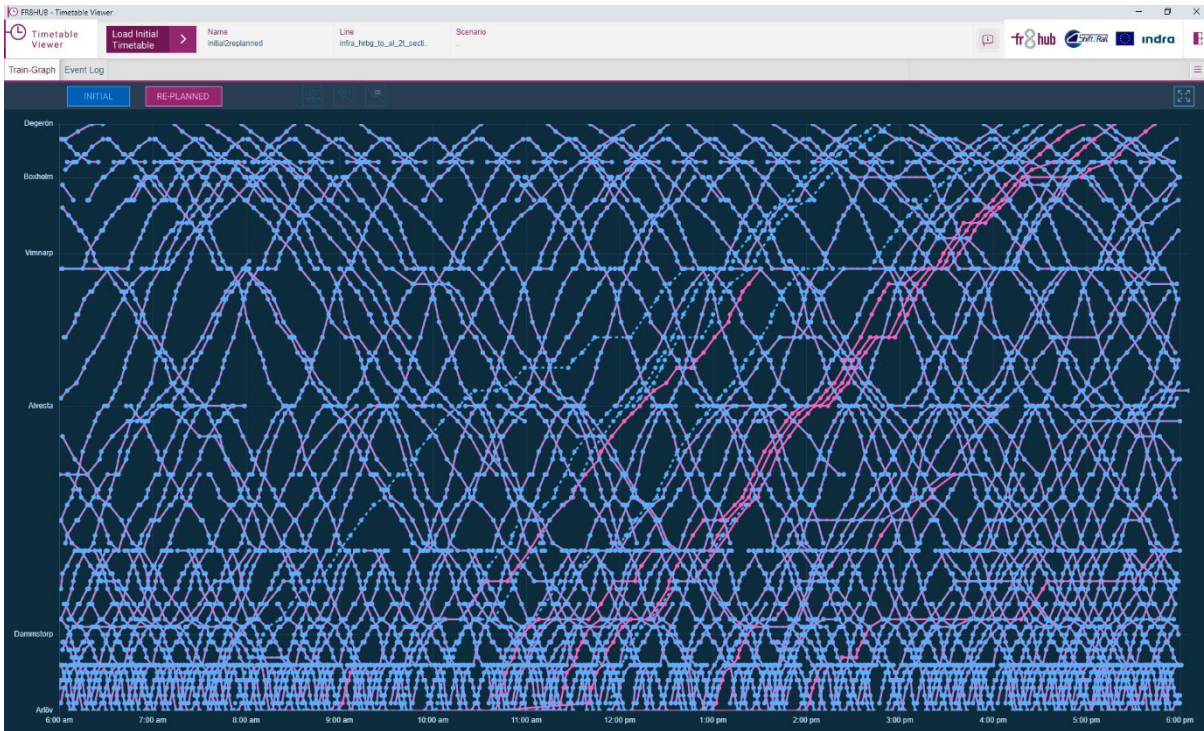
Figure 3: Comparison between the initial (blue) and the replanned (pink) timetable [FR8HUB, 2019]

The KTH module combines optimization and simulation in a loop (where simulation is done using the software RailSys) and can reschedule multiple trains at the same time (see Figure 4). Optimization is used to reschedule trains, while simulations provide information about the quality of a (potentially replanned) timetable. The output from the simulation can be fed back into the optimization so that the timetable quality can be further improved in the next loop. The iteration between simulation and optimization continues for as long as required by the scenario. The LiU module, intended for use close to operations, adds a new train to a timetable without affecting any other trains in the timetable. In Section 2.2, we discuss how the timetable modification module in this project builds upon the FR8HUB LiU algorithm.
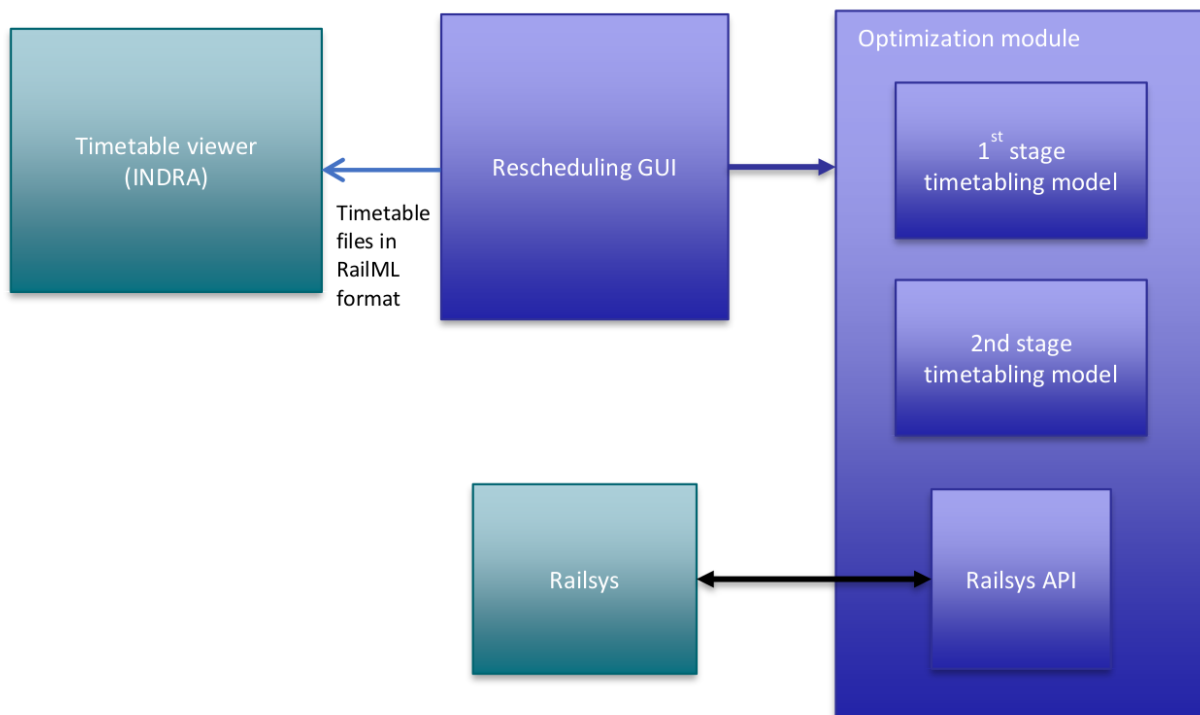
Figure 4: Architecture of KTH–Indra demonstrator [FR8HUB, 2019].

FR8RAIL III WP2

The demonstrator developed in FR8RAIL II WP3 (outlined in this document) is planned to be further enhanced in the upcoming Shift2Rail project FR8RAIL III WP2. In particular, in FR8RAIL III there will be a focus on demonstrating the planning of arrival yards of marshalling yards, and also how the planning of these can be integrated with the line planning.

2   Demonstrator scope

This section describes the aim and the functionality of the demonstrator. In fact, the demonstrator consists of two modules that by themselves can be considered as separate demonstrators. The first module is the *simulation module*, which consists of PRISM, while the second module is the *intelligent planning module*, which consists of an enhanced version of M2 and a program called TIMO (short for *Timetable Modifier*; developed within this project). The simulation module is also extended by M2 for visualization of simulation results.

2.1 Aim of the demonstrator

In general, the aim of the demonstrator is to demonstrate the advances and improvement possibilities for timetable planning and network management performed in TD5.2.1 *Improved methods for timetable planning* and also in TD5.2.3 *Real-time network management*. The demonstrator builds upon results from other Shift2Rail projects and will also be continued to be enhanced in future Shift2Rail projects.

To be more specific, the aim of the demonstrator developed in FR8RAIL II WP3 is:

- To provide a first step of the demonstrator for integrated planning of line and yard as outlined in the project ARCC.
- To develop and demonstrate new planning algorithms for short-term timetable planning.
- To demonstrate how macroscopic simulation can be used to evaluate timetables.
- To evaluate the usage of RailML for timetable planning [RailML, 2018].
- To evaluate the modular construction of the demonstrator and possibilities to extend it by external modules.
- To provide a basis for future demonstration projects in Shift2Rail.

2.2 Functionality

Using the simulation module, it will be possible to evaluate the robustness of a timetable. Simulation results may be visualized as graphical timetables. The timetable planning algorithms implemented in the intelligent planning module will be able to move trains within timetables, reschedule trains whose minimum runtimes have changed, and insert new trains into existing timetables. The role of PRISM, M2 and TIMO in the implementation of the simulation and planning functionality is described below.

Swedish PRISM model

PRISM is a macroscopic railway traffic simulation tool developed in the projects PLASA and PLASA-2. A detailed description of how PRISM works can be found in [Zinser et al., 2019]. In this demonstrator, the Swedish PRISM maintained by Trafikverket is used to simulate timetables. Aside from the timetables, information about train types and the infrastructure is needed as input. The differences between the Swedish PRISM model and the standard PRISM is that the Swedish model is based on Swedish input data, and that it has its own user interface.

The output from the Swedish PRISM model will be the simulation results for the simulated timetable(s). The output contains, among other data, the scheduled departure and arrival times and the actual departure and arrival times obtained in the simulation. The output will be

transferred to M2 for aggregation, analysis and visualization of the delays obtained in the simulation.

Since the Swedish PRISM model does not use the RailML format for its output files, a file format conversion is necessary when a simulation has been finished.

M2

In the demonstrator, the enhanced version of M2 (developed by the team from RISE) will produce a conflict-regulated timetable based on the original timetable from the infrastructure manager. No other timetable modifications will be performed by M2. The conflict-regulated timetable will be the starting point for modifications performed by TIMO. Apart from the conflict regulation, M2 will handle the following tasks:

- Managing a database that holds infrastructure and timetable data.
- Letting the user define the timetable planning problem to be handled by setting different parameters (see Section 4.1).
- Compiling the data of the problem (see Section 3) in (an extended version of) the RailML data format and handing them over to TIMO.
- Visualizing the modified timetable from TIMO (for example, by generating a graphical timetable where the conflict-regulated and the modified timetable can be compared).
- Aggregating and visualizing simulation results from PRISM (for example, by generating a graphical timetable where the planned and the simulated versions of the original timetable can be compared).

TIMO

The TIMO program is developed by the team from Linköping University. The goal of TIMO is to handle addition or reinsertion of train paths for (freight) trains, to begin with one (at a time). This could be a change of departure time from the departing marshalling yard or terminal (e.g., due to late train completion or the need to free marshalling yard capacity early), a change of arrival time at the arriving marshalling yard or terminal (e.g., due to capacity restrictions over the planned time of arrival), a change of the travel time (e.g., because the wagon load was altered, and a high/lower speed is possible), or the addition of a train path (which could have been moved from a previous day and constitutes a "new" train for the considered day). In particular, in TIMO, LiU aims to enable user-steered changes to train paths of other, existing trains in the timetable. For example, the user might allow that all trains from the same railway undertaking, all trains within a certain time window depending on the new allowed departure and arrival times, etc. may be adjusted to enable the new train path. In general, this strategy can allow for changes to the considered train path even in a very dense timetable, where such a change without modifying other train paths would not be feasible. Both by expanding the covered

scenarios (e.g., the change of train time) and by adding flexibility to some of the existing train paths, TIMO will expand on previous work like [Ljunggren et al., 2018]. The resulting timetable will be evaluated and visualized for comparison with the original timetable. While the algorithm developed in previous projects did not allow for integration with M2, TIMO will also be developed on macro level, and, hence, allow for integration.

TIMO algorithm overview

As input we have the timetable in RailML format; a number of trains, k, which should be moved/inserted (to start with, k=1); and a rule for which subset of other trains, S, we may move (trains from a specific railway undertaking, all trains ...).

In a first step we will transfer the RailML data to a data format that we can use for our algorithm. In case we move trains (and do not have newly-to-be-inserted trains as input), we will then construct a new timetable in which these trains are removed.

In our algorithm we will then choose a neighbourhood of trains around the time or time window for which the railway undertaking applied – our algorithm can choose different rules for choosing this neighbourhood. That is, we determine which trains from S – those which may be changed – will indeed be considered for changes. This will result in a number of trains, m, for which the train paths may be altered by our algorithm. Possible rules for choosing a neighbourhood of the subset of movable trains are, for example:

- Choose trains in a time interval around the given train(s)
- Choose x trains to both sides of the train(s)
- Choose x trains that would run after the train(s)
- Choose x trains that would run before the train(s)

It may also be possible to let the neighbourhood differ along the stretch of the train path.

Once the neighbourhood is chosen, the k given trains and the m trains we removed in the neighbourhood are to be inserted in the remaining timetable. Again, there are different methods to insert these trains, e.g.:

- Insert the trains one-by-one as early (or late) as possible (where we still need to choose the order in which the k new trains and the m existing trains are mixed)
- Move each of the m trains by a maximum temporal distance to either side

The resulting timetable (after inserting the *k+m* trains) can be evaluated according to several objectives, for example:

- Minimize the number of trains moved
- Minimize total time difference by which all trains were moved
- Minimize the maximum time difference by which any train is moved
- Minimize the time by which arrival times are moved
- Minimize the network load, i.e. the total time spent in the network by all trains.

As a last step, the output data, that is, the new timetable, must be transferred to RailML format.

2.3 Limitations

The demonstrator will have a number of limitations. The most important of these are the following:

- Since it is currently not possible to use the same IT environment for the simulation module and the intelligent planning module (see Section 5), the transfer of data between the modules will probably not be handled seamlessly. Instead, the user will have to take some manual actions to do the transfer (see Section 4).
- The infrastructure is not represented in detail in the data that are used by the intelligent planning module. For example, while the data indicate the number of tracks connecting every pair of neighbouring stations and the number of tracks at every station, there is no information about signals or how tracks are connected by switches. Similarly, the simulation module only models the interaction between trains in the railway network on a macroscopic level.
- The demonstrator will be developed to be able to handle any railway line in Sweden, but it will only be tested and verified on the Southern Mainline.
- The timetable modifications that the demonstrator can handle will not include all possible usages/modifications that a short-term train planner may have, but only the use cases outlined in this document.
- The rail yards will not be included in the demonstrator, even though we will assume that the trains depart from and arrive at marshalling yards. That is, the included railway network "starts"/"ends" just outside the yards.
- The aim of the demonstrator is to demonstrate the research results, concepts and advanced planning possibilities for domain experts (like line planners at IM). The intention is not that the demonstrator will be an operations tool for the possible users.
- The timetable visualization in M2 is not aimed for deep statistical analysis, but to illustrate a high-level timetable performance.
- The KPIs that are calculated should be seen as examples of KPIs. In a real setting, more advanced KPIs could be calculated.

3 Data

PRISM, M2 and TIMO will exchange different types of data with each other. All data exchanges will use an extended version of the RailML 2.4 format.

The data connection between PRISM and M2 is a "one-way" connection. To be able to perform visualizations, M2 needs the following data from PRISM, where infrastructure data and the original timetable, along with headway data, will have been provided to PRISM internally within Trafikverket's IT environment (by RailSys):

- Infrastructure data
    - Stations (and similar)
        - Name
        - Signature
    - Tracks between stations
        - Length
- Timetable data
    - Trains
        - Train number
        - Operating days
        - Stations and halts along the train route
            - Departure time and arrival time in the original timetable and in several simulations

The connection between M2 and TIMO is a two-way connection, where M2 supplies TIMO with all necessary data for calculations and TIMO provides M2 with results from calculations. M2 will provide TIMO with the following data:

- Infrastructure data
    - Stations (and similar)
        - Name
        - Signature
        - Tracks and their lengths
        - Concurrent entry
        - Headway times
    - Tracks between stations
        - Name
        - Length
        - Endpoints

- Headway times
- Runtime templates (minimum runtimes, depending on rolling stock formation, direction and stop pattern)
- Rolling stock data
  - Rolling stock formations
    - Maximum speed
- Timetable data
  - Trains
    - Train number
    - Railway undertaking
    - Rolling stock formation(s)
    - Operating days
    - Stations and halts along the train route
      - Whether a stop at the station or halt is mandatory (demanded by the railway undertaking), possible or impossible
      - Departure time and arrival time in the original and in the conflict-regulated timetable
      - Whether the train stops or passes in the original and in the conflict-regulated timetable (in case a stop is possible but not mandatory)
      - Whether an arrival or departure time in the original timetable should be kept (as well as possible) in the modified timetable (for example, due to a delivery commitment from the infrastructure manager to the railway undertaking)
    - Tracks used between pairs of consecutive stations and halts
- Scenario-defining parameters (see Section 4)

After having modified the timetable, TIMO will provide M2 with timetable data for the modified timetable (corresponding to the data it received for the original timetable and the conflict-regulated timetable) together with some KPIs from the timetable modification.

4   Test scenarios and use cases

The demonstrator and its algorithms will be tested on several scenarios describing situations where timetable modifications are needed. This section contains these scenarios and two use cases that describe the interaction between the user and the demonstrator, as well as the processing performed by the demonstrator. Furthermore, the section contains a discussion of ways to measure timetable quality.

4.1 Test scenarios

The scenarios will be based on real data and will have the following characteristics in common:

- Part of the railway network:
  - Hallsberg–Malmö line, Sweden
  - Hallsberg marshalling yard (HRBG) and Malmö marshalling yard (MGB). Both these yards are on the border of the selected part of the network, however none of the yards are in detail explicitly included in the modelled network, e.g. the yard layout and yard capacities are out of scope.
- Time:
  - Yearly timetable providing the original timetable data: T16 (2016)
  - Primary date: Thursday, 13 October 2016
  - Period of time covered by each scenario: 24 hours
- Included trains:
  - All trains Malmö–Hallsberg and Hallsberg–Malmö, including trains travelling only a part of the line.
- Timetable modification:
  - The added/changed train (according to scenarios a–d) will be a freight train in the southbound direction, from HRBG to MGB.
    Exact train or time windows, etc., will be defined in a later stage, when the details of the timetable have been studied.

Scenario extensions:

- **Days with less or more traffic**: In addition to the default date as explained above, the scenarios can be run on dates with dense or sparse traffic. A sample date with sparse traffic is e.g. Saturday, 15 October 2016.
- **Northbound trains**: The basic scenario is that the train to be modified is southbound, from HRBG to MGB. However, an extended scenario is to modify a train in the northbound direction, and/or to allow modification in northbound direction when inserting southbound traffic.

Test scenarios for the simulation module

The main test scenario for the simulation module is as follows:

a) Analyse timetable robustness
   The robustness of a railway timetable that includes e.g. trains and maintenance should be analysed. Using the simulation module, Swedish PRISM Simulator is used to make a sufficiently large number of simulations on macro-level, each of them generating a "resulting timetable" corresponding to a possible timetable outcome from operations. The simulation results are evaluated using the statistical toolset provided in PRISM.

A possible extension of this scenario is:

> The results from the simulation are imported into M2 for visualization. The visualization is based on a graphical timetable view, in which the nominal timetable is illustrated as well as how the outcome of the timetable is "spread" around the nominal timetable.

Scenario parameters:

- Timetable to be analysed (geography and dates).
- Number of simulations performed by the simulation module.
- Statistical measures to be used for timetable analysis.
- Railway line to visualize in graphical timetable.
- Statistical measures to be visualized in graphical timetable.

Test scenarios for the intelligent planning module

There will be three basic test scenarios for the intelligent planning module. Extensions of these scenarios may be added as the project evolves.

a) **Change departure time of a train**

At the departure yard, something has occurred so that the departure time of a train needs to be changed (e.g. late incoming train). The change can be either forward or backward in time, but the time change is less than X hours (otherwise the train is considered as a new train, see scenario d) below). The new timetable for the train shall adhere to some defined departure time window, but also possibly to some arrival time window of the train. The move should be made according to some criteria, e.g. move train to the most robust timetable channel. When the train is changed it is possible to define how other trains are allowed to be moved in order to give room for the changed train.

Scenario parameters:

- Train to be moved (train number and date).
- "Optimization criteria" for changed timetable of train.
- Time window for departure. (Potentially, there are several time windows possible.)
- Time window for arrival. (Potentially, there are several time windows possible.)
- Which other trains that are allowed to be altered in the timetabling process
- How much other trains can be moved.
- Restrictions in the move of other trains e.g. certain stations at which train must not change arrival/departure times.

b) **Change arrival time of a train**

At the arrival yard, something has occurred so that the arrival time of a train needs to be changed (e.g. yard is very heavily occupied). The change can be either forward or backward in time, but the time change is less than X hours (otherwise the train is considered as a new train, see scenario d) below). The new timetable for the train shall adhere to some defined arrival time window, but also possibly to some departure time window of the train. The move should be made according to some criteria, e.g. move train to the most robust timetable channel. When the train is changed it is possible to define how other trains are allowed to be moved in order to give room for the changed train.

Scenario parameters:
Same as for scenario a).

c) **Changed runtime of a train**

The minimum runtime of a train is changed e.g. due to changed load of the train or changed locomotive type compared to the timetable specifications. This corresponds to that the train gets a new runtime template. The new timetable for the train shall adhere to some defined arrival time window, but also possibly to some departure time window of the train. The timetable change should be made according to some criteria, e.g. move train to the most robust timetable channel or arrive as soon as possible or minimize number of stops along the trip. When the train is changed it is possible to define how other trains are allowed to be moved in order to give room for the changed train.

Scenario parameters:
- Train to be rescheduled (train number and date).
- The new runtime template(s) applicable for the train.
- "Optimization criteria" for how the train is rescheduled.
- Departure yard and time window for departure. (Potentially, there are several time windows possible.)
- Arrival yard and time window for arrival. (Potentially, there are several time windows possible.)
- Which other trains that are allowed to be altered in the timetabling process.
- How much other trains can be moved.
- Restrictions in the move of other trains e.g. certain stations at which train must not change arrival/departure.

A fourth scenario is also relevant, but is considered as having lower priority in the project:

d) **Add train to timetable**

There is a need to add a train to the timetable. The train may be a train that is moved from one day to another or a new transportation need. The added train shall adhere to a specific departure time window from the origin yard and another arrival time window at the destination yard. The train should be added to the timetable in a way that fulfils some criteria, like adding the train in the most robust path or minimizing changes of other trains. For adding the train, it is possible to define how other trains are allowed to be moved in order to give room for the added train.

Scenario parameters:
- Train to be added (train route and date).
- "Optimization criteria" for inserting train.
- Train type to be added, i.e. which runtime template is applicable for the train.
- Departure yard and time window for departure. (Potentially, there are several time windows possible.)
- Arrival yard and time window for arrival. (Potentially, there are several time windows possible.)
- Which other trains that are allowed to be altered in the timetabling process.
- How much other trains can be moved.
- Restrictions in the move of other trains e.g. certain stations at which train must not change arrival/departure.

4.2 Use cases

The following two use cases describe the interaction between the user and the demonstrator, as well as the processing performed by the demonstrator. In the first use case, the simulation module is used to evaluate (and visualize) the robustness of an existing timetable. In the second use case, the intelligent planning module is used to perform minor timetable modifications. In the descriptions of the use cases, one or several steps may be automated so that no user interaction is needed to perform the steps.

Use case 1

PRISM

1. User creates Prism input file. This is based on timetable, traffic (disturbances) and infrastructure data.
2. User starts PRISM, opens the input file and sets relevant options.
3. PRISM performs the simulation and creates an output file containing the original timetable, the simulated version of the timetable and associated data (see Section 3).
4. User evaluates the result of the PRISM simulations.

A planned extension of use case 1 is to visualize the simulation results in M2. However, currently an investigation of the IT security regulations is performed which may result in that

the extension is not possible. The extension includes the following steps:

5. User transfers the output file(s) to outside Trafikverket's firewall.
6. User converts the output file(s) to RailML format using a conversion script.

M2

7. User imports the simulated timetable(s) and associated data into M2.
8. User selects which timetable and which geographical line to visualize.
9. M2 aggregates the simulation results and calculates suitable statistics (e.g. mean, median and standard deviation of the resulting delays.
10. User selects what kind of statistics that should be visualized.
11. M2 displays graphical versions of the timetable(s) illustrating the simulation results.
12. User ends M2.

Use case 2

M2

1. User starts M2.
2. User selects timetable (T16), date (Thursday, 13 October 2016) and time period.
3. User selects the line Hallsberg–Malmö.
4. User selects which type of scenario to run (see Section 4.1).
5. User sets parameters for the timetable modification (see Section 4.1).
6. User selects time period and part of the railway network to visualize as graphical timetables.
7. M2 produces a conflict-regulated timetable based on the original timetable.
8. M2 compiles input data and parameters for the timetable modification, writes them to a file in RailML format and starts TIMO.
   TIMO
9. TIMO reads input data and parameters for the timetable modification.
10. TIMO modifies the timetable in the selected way.
11. TIMO produces output data and writes it to a RailML file. Output consists of a new (modified) timetable (and some quality measurements – see Section **Fel! Hittar inte referenskälla.**).
12. TIMO sends a signal to M2, indicating that the processing is finished. (Alternatively, M2 monitors a folder to see when a new file has been stored there.)
   M2
13. M2 reads the modified timetable produced by TIMO.
14. M2 displays graphical versions of the two timetables (the conflict-regulated and the modified).
15. User inspects the changes made to the timetable.

4.3 Quality measurements for timetables

The two main concerns when deciding whether to accept or deny train path changes close to

operations are (1) how the change may affect other trains, and (2) to what extent the wanted changes can be realized. For this we may need several quality measurements or Key Performance Indicators (KPIs), some of which may be included in the "optimization criteria" (see Section 4.1 above).

The main service quality indicator on the day of operation is punctuality at geographies that are of commercial interest. We call these geographies in combination with their promised arrival or departure time *delivery commitments* (as they represent the service that the IM has committed to deliver when establishing the timetable). For example, it is a delivery commitment that a passenger train should arrive to a station with passenger exchange at or before its established arrival time, and freight trains should arrive on time for loading/off-loading. Associations are also delivery commitments. That is, if there was a planned passenger or wagon connection in the published timetable, then this connection should be upheld during operations. Associations and stops for, e.g., locomotive turning, wagon decoupling, staff breaks etc. are also delivery commitments.

Note that train path changes close to operations can have both negative and positive effects on the overall transport quality. For example, if a train path is moved out of a peak period then the robustness of the timetable might improve. Improved robustness decreases the risk of delays and increases the chance of good transport quality. On the other hand, if a train path is moved into a peak period the robustness might decrease and the risk of delays (and poor transport quality) increases. Moving a train path may also result in an increased risk of delays for some trains while simultaneously decreasing the risk of delays for other trains. An early departure may give an increased flexibility for later (operational) rescheduling, but may also incur costs in terms of network capacity and potentially blocked sidetracks.

To complicate the situation even further, depending on the freedom granted to the replanning algorithm, delivery commitments may be broken in the updated timetable. That is, we plan on breaking some delivery commitments (*planned delays*). Trains with planned delays obviously run a large risk of not delivering as promised. However, knowingly breaking the delivery commitments for some trains to improve the quality of others may still be preferable. Especially as the cost of delay varies a lot, both when it comes to size and shape. For example, the cost run up by a delayed freight train may be fairly linear up until the point where the wagons miss their connecting train or ship, at which point a very high cost is incurred. Likewise, arriving late (and thereby breaking the delivery commitment) to an interim station where not many people alight may be considered better than arriving late to the final destination of the train where many people alight.

To estimate the effects of a timetable change on the traffic outcome, different timetable measurements can be analysed. Deciding which measurements to include is part of the research. A good selection should both capture different quality aspects that are considered important and

have a strong correlation (and preferably a causal relationship) with the traffic outcome. For an overview of relevant aspects, see [Gestrelius et al., 2019]. An introduction to KPIs used in the literature is given by [Nicholson et al., 2015]. The Swedish infrastructure manager has published timetabling rules that should ensure a certain degree of robustness (see e.g. [Trafikverket, 2016], [Trafikverket, 2017] and [Trafikverket, 2018]). Ensuring that the changed timetable abides by these published rules is therefore a sensible first quality measurement. Examples of other quality measurements are given below.

KPIs for measuring planned delays are e.g.,

- the number of broken delivery commitments,
- the maximum planned delay time for any delivery commitment,
- the cost of planned delays (if some sort of priority value or cost has been provided, either by the railway undertakings or by the infrastructure manager).

Examples of robustness measurements are,

- % of buffer times that are smaller than a given threshold,
- % time supplements for each train,
- sum of shortest headway reciprocals (SSHR),
- sum of shortest arrival reciprocals (SSAR),
- number of overtakings on single and double tracks,
- meetings on single tracks.

When it comes to measuring how good the changed train path is, the following measurements could be used:

- temporal distance from the requested change,
- cost of the distance from the requested change (recall that the cost of delays is likely to be nonlinear),
- the change in cost for handling the train in the arrival/departure yard (e.g. the cost of the yard time window that was selected).

Other KPIs that do not necessarily relate to transport quality but that may still be interesting for getting an overall understanding of the timetable is the number of trains, the speed homogeneity of the trains and the distribution of non-occupation time intervals. Non-occupation time intervals, often called *white times*, are time intervals when a track is not occupied. White times are a measure of residual capacity which is especially important if more trains may be added to the timetable later on.

Rather than making measurements directly on the timetable, simulation can be used to estimate the effects of a timetable change on the traffic outcome. Deterministic simulation can be used

for identifying timetable infeasibilities and stochastic simulation based can be used to analyse the robustness of a timetable. In this project, the Swedish PRISM simulator is going to be used to evaluate the robustness of the original timetable.

5 High-level architecture and data communication

As mentioned in Section 2, the demonstrator will consist of two modules: the intelligent planning module and the simulation module (see Figure 5). In turn, the intelligent planning module will include M2, TIMO and a script for conversion of data between the data format used by PRISM and the RailML format. Furthermore, M2 must have access to the optimization software CPLEX Optimizer in order to produce conflict-regulated (and, in other settings, optimized) timetables. The simulation module will consist of PRISM.

M2 consists of five main parts: a central part for generation and handling of problem instances (timetable planning problems and resulting timetables), a part for optimization and conflict regulation according to different objective functions, a part for conversion of problem instances between the internal representation used by M2 and the RailML format, a graphical user interface where the user can define the problem to be solved by setting different parameters and where timetables are visualized, and a database holding infrastructure and timetable data (mainly from Trafikverket's system TrainPlan).

As described in Section 4, the data communication between PRISM and M2 will require some manual intervention. This is because PRISM must be run in Trafikverket's IT environment, while the other software must be run outside it, and because data must enter and leave Trafikverket's environment in a secure way, through a firewall. Therefore, the arrow in Figure 5 that indicates the data communication between M2 and PRISM is dashed.
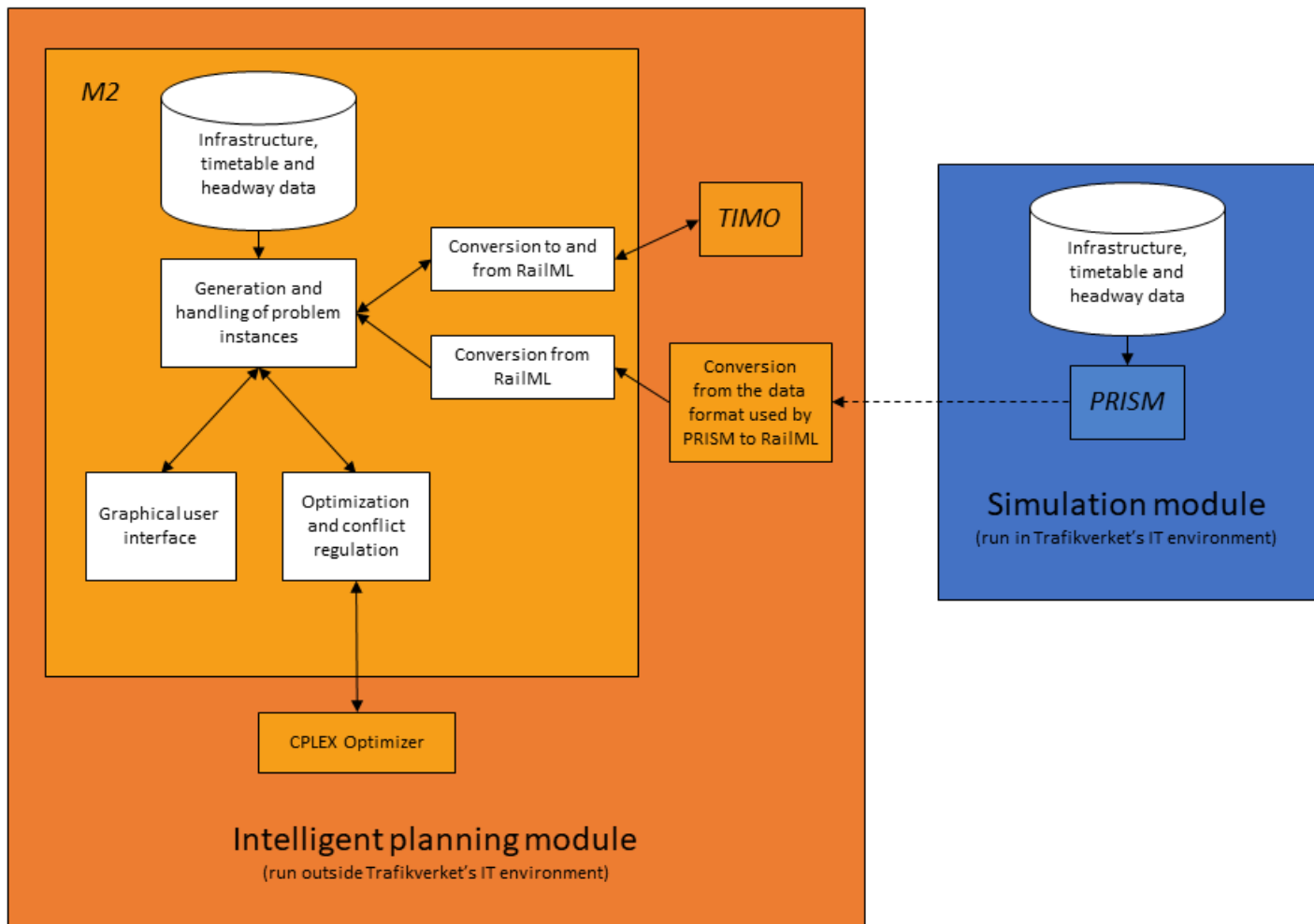
Figure 5: Architecture of the demonstrator

6   IT security

Trafikverket has rules and regulations about IT security that the project needs to follow. Data information received by or taken from Trafikverket's information systems needs to be agreed by Trafikverket and to follow Swedish law on IT security.

The FR8RAIL II demonstrator consists of:

- M2 capacity planning and optimization tool developed by RISE.
- TIMO for timetable optimization. TIMO is connected to M2.
- PRISM Swedish macro simulator. PRISM is not directly connected to M2 and runs in an IT environment at Trafikverket.

M2 gets infrastructure data and timetable data from TrainPlan. PRISM gets infrastructure data and timetable data from RailSys.

6.1 IT security and IT environment

For PRISM, an IT environment is currently being established at Trafikverket.

For M2, Trafikverket will start dialogue with RISE about IT security, IT environment, IT architecture and data security.

6.2 Data security

M2 infrastructure and timetable data must be approved by Trafikverket. Trafikverket has received information from RISE about M2 infrastructure and timetable data in December 2019. The task is to secure that M2 only contains data that follow Swedish law on data security.

This activity will be led by responsible persons within Trafikverket about M2 and responsible persons about data security at Trafikverket. Currently, this group is being established at Trafikverket. This group will have dialogue with RISE about data security for M2.

6.3 M2 historical data and headway times

The data from Trafikverket that will be used by the demonstrator are historical. The intelligent planning module will use data describing planned traffic for a certain period of time and the corresponding infrastructure (represented on a macroscopic level). The disturbances applied by the simulation module will be sampled from a probability distribution based on operative data. The demonstrator will also use Trafikverket's guidelines for headway times in timetable construction.

7 Summary, timeplan and risks

7.1 Summary and conclusions

The demonstrator in FR8RAIL II WP3 consists of two parts: the intelligent planning module and the simulation module.

The intelligent planning module has two parts: M2 and TIMO, while the simulation module consists of PRISM Swedish macro simulator.

M2 current status:

- M2 is developed by RISE.

- Includes a database for infrastructure, timetable and headway data.
- Has functionality for optimizing timetables.
- A specified connection to TIMO (this connection will be developed in this project).
- Will have a link to PRISM, how this link will be needs further investigation.

TIMO current status:

- TIMO is developed by Linköping University.
- Handles rescheduling of (freight) trains.
- TIMO builds upon results from the FR8HUB project that will be further developed in this project.

Simulation module, PRISM Swedish macro simulator, status:

- PRISM Swedish macro simulator is developed by Trafikverket in co-operation with KTH. The kernel is developed by DB.
- PRISM has data for infrastructure, timetable and capacity.
- PRISM Swedish macro simulator has a link to RailSys.
- How to exchange files between PRISM and M2 needs to be further investigated.

Information security and IT security status:

- M2: To be able to export data from M2 we need to secure that M2 fulfils Trafikverket's IT security requirements and Swedish law. A dialogue has started between Trafikverket and RISE about IT security for the M2 research demonstrator to be used in the FR8RAIL II and FR8RAIL III projects.
- PRISM Swedish macro simulator: An IT environment is currently being established at Trafikverket. PRISM is a proof of concept within Trafikverket. IT security is followed according to regulations within Trafikverket.
- When PRISM and M2 have been evaluated, it will also be evaluated if a connection between PRISM and M2 is possible with respect to Trafikverket's IT security requirements and Swedish legislation.

7.2 Time plan

Below is a time plan for the continuation of the project. IT security requirements will have some impact on the final demonstrator result.

Step	Deadline	Responsible	2020 F M A M J J A S O N D	2021 J F M A
Milestone 3.1	February 2020	RISE		
Investigation of how Trafikverket's IT security requirements and Swedish legislation will affect M2	April 2020	TrV		
Investigation of how Trafikverket's IT security requirements and Swedish legislation will affect PRISM/RailSys	April 2020	TrV		
Adaptation to Trafikverket's IT security requirements and discussions with Trafikverket about new data for M2	April 2020	RISE		
Establishment of an IT environment for PRISM at Trafikverket	April 2020	TrV		
KTH Prism, use case and IT specifications	April 2020	KTH		
KTH Prism, research method development and IT	May 2020	KTH		
Investigation of the possibility to transfer data from PRISM, through Trafikverket's firewall	April 2020	TrV		
KTH Prism, simulations and analysis	December 2020	KTH		
Implementation of data transfer from PRISM, through Trafikverket's firewall (optional)	April 2020	TrV		
Implementation of import of PRISM data into M2 (optional)	April 2020	RISE		
Delivery of TrainPlan data from Trafikverket to RISE	April 2020	TrV		
Delivery of example output from TIMO to RISE	April 2020	LiU		
Script for conversion from PRISM format to RailML ready	May 2020	KTH		
Delivery of preliminary result data from PRISM to RISE (optional)	May 2020	KTH		
Prototype of communication and timetable modification functionality in TIMO	May 2020	LiU		
Adaptation of M2's user interface	May 2020	RISE		
Implementation of the connection between M2 and TIMO	May 2020	RISE		
Delivery of real result data from PRISM to RISE (optional)	June 2020	KTH		
Implementation of aggregation and analysis of PRISM data in M2 (optional)	September 2020	RISE		
Final functionality in TIMO	October 2020	LiU		
Verification of functionality, internal testing finished	November 2020			
Demonstrator ready for validation, i.e. planning functionality complete so that it can be evaluated	December 2020			
Demonstrator finished	February 2021			
Validation finished	March 2021	LU		
Project demonstration for Trafikverket/Shift2Rail	March 2021			
Delivery D3.4	April 2021			

7.3 Risks and consequences

An important conclusion of this milestone is that IT security needs to be further investigated. The outcome of this investigation will have impact especially on the connection between PRISM and M2. PRISM and M2 will have a loose or no connection. This will be further studied during the next few months.

The workplan of the project has been modified and updated due to IT security requirements from Trafikverket and Swedish legislation on IT security. The risk matrix below, where risks in the project are evaluated according to the "minirisk" process, has been adapted to these changes.

Factor	Consequence (1–5)	Probability (1–5)	Weighted risk
Regulations regarding information security and data sharing will further affect the workplan	3–5	3	9–15
Inconsistent data because of several data sources	2	3	6
Lack of personnel	3	3	9
Key personnel changed	4	2	8
Different expectations on project result	2	2	4

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