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EXECUTIVE SUMMARY

This document aims to provide guidelines for the practical implementation of the different subsystems of a MERLIN-based railway electrical smart grid. In addition, those results of project MERLIN (especially from WP2 and WP6) are systemized and organized.

For each of these subsystems, a brief description is provided centred on their functionality, their inputs and outputs. Its primary purpose is to identify the main information exchanges, which are inherent to the idea of the Smart Grid. It should be noted that the volume of new information flows are significantly larger than in traditional electrified railways and for that reason, their practical implementation is also one of the big technical challenges to be faced (especially, in railways with insufficient communication capacities).

Due to the large amount of investment required, the implementation of a railway smart grid will be done progressively: the smart trains and the smart infrastructure will have to coexist with traditional trains and traditional infrastructures. Furthermore, the concept of “smart” train and infrastructure will evolve as new functionalities are added. In order to provide some criteria for progressive implementation, this guide describes the interdependencies among the subsystems specified in MERLIN and suggests implementation in phases, when it is possible.

The full adoption of these technologies implies a change of paradigm in the way electrical railways are designed and operated and therefore, in the decision making processes (i.e. in the procedures of the railway companies). For that reason, this guide includes a brief description of the decisions to be made in every temporal horizon and how the different subsystems of MERLIN can support them.

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LIST OF ACRONYMS

ATO	Automatic Train Operation
CA	Contractual Arrangements
DAO	Day Ahead Optimisation
DER	Distributed Energy Resources
DOEM	Dynamic Onboard Energy Manager
DSO	Distribution System Operator
EBDM	Energy Buyer Decision Maker
EC	External Consumer
EMO	Electricity Market Operator
EMS	Energy Management System
ESS	Energy Storage Systems
GOS	Global Optimisation Software
IM	Infrastructure Manager
LOS	Local Optimization Software
MAO	Minute Ahead Optimisation
PCC	Point of Common Coupling
REM-S	Railway Energy Management System
RSST	Reversible Substation
RTO	Real Time Operation
RU	Railway Undertaking
SCADA	Supervisory Control and Data Acquisition
SDMT	Strategic Decision Making Tool
SST	Substation
ATO	Automatic Train Operation
CA	Contractual Arrangements
TSO	Traffic System Operator
VPP	Virtual Power Plant

1. INTRODUCTION

This document aims to provide guidelines for the practical implementation of the different subsystems of a MERLIN-based railway electrical smart grid. In addition, those results of project MERLIN (especially from WP2 and WP6) are systemized and organized.

For each of these subsystems, a brief description is provided centred on their functionality, their inputs and outputs. Its primary purpose is to identify the main information exchanges, which are inherent to the idea of the Smart Grid. It should be noted that the volume of new information flows are significantly larger than in traditional electrified railways and for that reason, their practical implementation is also one of the big technical challenges to be faced (especially, in railways with insufficient communication capacities).

Due to the large amount of investment required, the implementation of a railway smart grid will be done progressively: the smart trains and the smart infrastructure will have to coexist with traditional trains and traditional infrastructures. Furthermore, the concept of “smart” train and infrastructure will evolve as new functionalities are added. In order to provide some criteria for progressive implementation, this guide describes the interdependencies among the subsystems specified in MERLIN and suggests implementation in phases, when it is possible.

The full adoption of these technologies implies a change of paradigm in the way electrical railways are designed and operated and therefore, in the decision making processes (i.e. in the procedures of the railway companies). For that reason, this guide includes a brief description of the decisions to be made in every temporal horizon and how the different subsystems of MERLIN can support them.

This section provides a brief overview of the concepts developed in the MERLIN project (subsection 1.1) defining the new approach from an end-user’s perspective (sub-section 1.2).

1.1 OVERVIEW OF MERLIN ARCHITECTURE

The MERLIN project provides a framework of technologies that allow integrated management to achieve more sustainable and optimised energy use in European electrical mainline railway systems. The structure for MERLIN is shown in Figure 1 below:

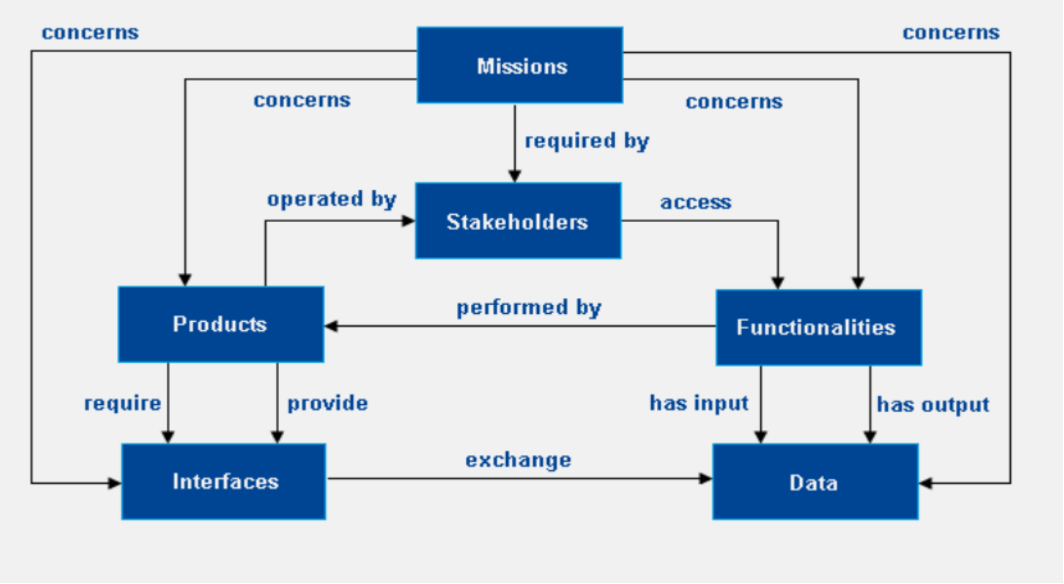

Figure 1 : CoralTree architecture for MERLIN.

To achieve its goals, an holistic approach has been taken in MERLIN which is twofold: (i) for the long-term management of railways, an off-line tool –the SDMT– is used to support the strategic decision making and (ii) for the short term (covering from 24/48 hours ahead to real time), an operational tool – REM-S– is in charge of controlling the electrical railway system.

A) The SDMT

The SDMT is intended to be a decision support system for the analysis and investment planning related to energy usage, overall life cycle costs and predictive behaviour of the operational Railway Energy Management System (REM-S). More specifically, this system targets the strategic decisions required when designing new railway systems or carrying out significant modifications to existing systems, such as timetable changes, new rolling stock or electrification.

Several missions can be defined to reflect the factors that must be optimised together to achieve the overall objective of improving the efficiency of strategic decisions:

- energy use parameters (energy consumption, power level and energy cost).
- life cycle costs.
- capacity.
- load factor (which is affected by total journey time, service frequency, dependability and other factors)

A detailed description of the SDMT, including its objectives and its architecture, can be found in the document *(4)*.

B) The REM-S

The REM-S is an integrated solution aiming to achieve more sustainable and optimised energy usage in European electric mainline railway systems. This can be obtained through a system monitoring the energy consumptions of the different subsystems of the railway network and their components and suggesting a “smart” solution for the optimisation of use of energy in the different parts of the system aiming to achieve the overall benefit of the railway system.

The three Operational REM-S missions described as optimisation are:

- To optimise the energy consumption needed for operating the railway system ensuring the fulfilment of the applicable performance requirements.
- To optimise the power demand needed for operating the railway system ensuring the fulfilment of the applicable performance requirements.
- To optimise the costs relevant to energy consumption needed for operating the railway system ensuring the fulfilment of the applicable performance requirements.

Optimisation is performed at two different levels:

- at network level: there is a high level optimisation, taking into account the duration of the next day (configurable) and without being in contact with each element of the network;
- at the local level: a minute ahead optimisation is carried out.

A detailed description of the REM-S, including its objectives and its architecture, can be found in the document *(2)*.

1.2 THE MIGRATION TO A SMART GRID FROM THE USER’S PERSPECTIVE

In addition to the investments in new equipment, the implementation of the MERLIN technologies will modify the way railways are operated, both from the Infrastructure Manager (IM) and the Railway Undertaking (RU) sides.

A) Infrastructure Manager

In traditional railway systems, the daily operation (i.e. the schedules, the way trains are driven, the way the electrical grid is set up, etc.) is typically established months in advance for each day type (typically, for each season, i.e. summer/winter, working days/weekends/holidays, etc.). The implementation of MERLIN-based technologies allows the IM to fine tune the operation (change the driving styles to achieve an optimal operation) as the expected circumstances change.

The day before, a first adjusting process is carried out to determine the way each train is driven (among a list of driving styles supplied by the RU) and each energy regulating device (DERs, ESSs, etc.) is operated to achieve a global optimum. In parallel, the purchase of the electricity is optimized, based on an available portfolio of procurement options (which includes transactions in the electricity spot markets and by means of contractual arrangements) and the expected operation. To carry out these optimizations, the IM needs to collect information about the expected circumstances (such as weather forecasts, electricity price forecasts, DERs power production forecasts, expected changes in the infrastructure or the trains services, etc.) from the RUs and from other specialized forecast providers.

A few hours in advance, as the circumstances may change (for instance, a specific substation may become unavailable) and new forecasts may be available (providing more accurate information), these optimizations can be launched again to adjust the operation, if deemed necessary. In this timeframe, the electricity spot markets allow the amount of energy previously purchased to be corrected by means of the intra-day sessions.

When less than an hour in advance (minutes ahead), a second level of optimization is carried out locally to ensure the optimized operation instructions are followed in each zone. When deviations occur, the control system can correct them by modifying the operation of the manageable elements (trains, ESSs, DERs and other loads).

In the approach proposed in MERLIN, the following tasks are carried out by the IM:

- Estimation of the average energy prices, for the following days.
- Global optimization of the operation (one day in advance, for the forecasted conditions), which determines the way manageable elements (trains, other loads, ESSs, DERs, etc.) will be operated.
- Optimization of the electricity procurement (one day in advance, for the forecasted conditions and the optimized operation –which is stochastic), among the portfolio of procurement alternatives. Purchase of the energy.
- If deemed necessary (e.g. the forecasted demand or prices change significantly), the previous optimization can be re-launched.
- Purchase/selling of the energy (few hours in advance). This step may be very relevant if the forecasted demand or prices change significantly.
- Local optimization of the operation (minutes in advance), which determines the best way to operate the elements (trains, ESSs, DERs, etc.) within a zone.
- Real time operation (seconds in advance), which determines the best way to operate the faster elements (such as the ESSs, etc.) to correct in real time the deviations that may occur.
- Billing, which takes into account that not all the energy transferred has the same price. For instance, the energy consumed by a train following the instructions from the control centre to optimize the overall operation may have a different price that the energy consumption planned initially.

To implement the smart grid technologies which allow this smart operation, the IM must:

- Acquire the TI systems that perform these optimizations, which are described in detail in documents *(4)* (architecture of the SDMT) and *(2)* (architecture of the REM-S). Also, the existing control systems will have to be updated to support the new features the smart grid can provide (for example, by updating the human-machine interfaces).
- While part of the required information may be collected or generated by the IM itself, important information also comes from the RUs and other external providers (e.g. meteorological forecast providers, electricity spot markets forecast providers, etc.). Thus, the communication channels with these entities must be defined and, in the case of the external providers, the forecast services purchased.

- Train the personnel of the control centres in the new concepts and the new tools used in the smart grid operation. In some cases, these teams may need to be reinforced.

B) Railway Undertaking

In traditional railways, RUs operate the trains trying to reduce the overall energy consumption, while satisfying the schedule. In MERLIN more attention is paid to the infrastructure limitations in such a way that RUs, in addition to their role as an energy consumer, may also act as a “flexibility” provider. In other words, the RUs may offer different power profiles (which normally means different driving styles) so that the IM can choose among them. In exchange of this availability to change driving style on request, the RU may be compensated economically. This flexibility of train driving is not trivial and requires new driving assistance systems to allow the system to react in real time (re-optimizing the driving for the new conditions).

In the approach proposed in MERLIN, the following tasks are carried out by the RU:

- Determining a reduced set of driving instructions (driving strategies) for each trains service, each time the IMs requests it (normally, one day in advance or when the operation changes significantly and a new global optimization is to be launched). To determine driving for each journey driving, an optimization is normally carried out to optimize its power profiles (e.g. to minimize the energy consumption).
- Purchasing the energy from the IM or to another external energy supplier. It should be noted that, in addition to the energy exchanges, an electricity distribution service is provided by the IM (the provider of this service cannot be freely chosen).
- When the REM-S minutes ahead optimization needs to adjust the operation, the RUs are requested to offer flexibility (i.e. availability to perform the requested changes, such as power limitations or new driving styles for the next period, etc.). Each RU must determine in real time which flexibilities can or cannot be offered.

To implement the smart grid technologies which allow this smart operation, the RU must:

- Acquire the TI systems that perform journey driving design, which are described in detail in document *(3)* (architecture of the DOEM). In addition, the acquisition of ATO systems or, at least driving assistance systems, supporting the new features defined in MERLIN is also necessary.
- Enable communication channels with the IM to allow the information flows required by the smart grid.
- Train the personnel in the new concepts and the new tools used in the smart grid operation.

It should be noted that new types of railway undertaking may appear in the new context (for example, ESS operator), that provide the flexibility as a service. Similar requirements would apply to these entities.

1.3 Dependencies

Table 1 shows the dependencies between the main systems of MERLIN (the SDMT and the REM-S), which in fact are uncoupled. The SDMT runs off-line, to optimize strategic decisions (normally, in the long term), which just requires an external simulation tool (a multi-train simulator) to evaluate the energy consumptions. The REM-S manages the operation of the electrical railway in real time and, for that purpose, does not need to perform any strategic decision optimization.

Table 1. Main systems in MERLIN- Dependencies.

	SDMT	REM-S	Multitrain simulator (external)
SDMT		Not required	Required
REM-S	Not required		Required

1.4 DEPLOYMENT

As explained above, the SDMT and the REM-S are independent and, therefore, their implementation can be carried out independently. Their use can be complementary, as they perform optimisation at different levels.

2. THE STRATEGIC DECISION MAKING TOOL

2.1 GENERAL DESCRIPTION

As shown in Figure 2, the SDMT is composed of three modules (Contractual Arrangements, Core and user interface and Optimisation Algorithm) which interact with a number of external tools for the simulation of railway systems and the calculation of energy flows within their power network. These modules are described in detail in *(4)*.

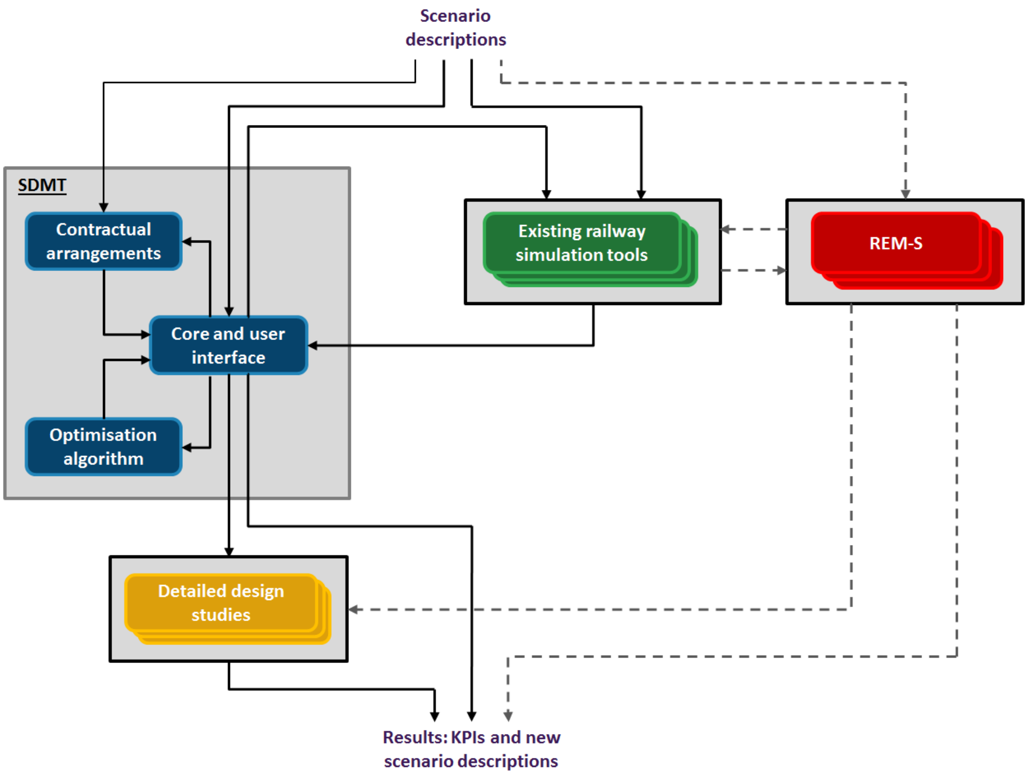

Figure 2 : SDMT modules

2.2 CONTRACTUAL ARRANGEMENTS MODULE

The main aim of the Contractual Arrangements (CA) Module is to calculate the cost of operating each configuration of the railway system (scenario) referenced to a defined timetable. The cost of the energy (plus special charges from the energy supplier or other service supplier) to carry out this operation within a specified time horizon will be considered as energy cost or cost operation.

The CA module receives detailed parameterisation of the electrical power profiles at each substation, as well as the contractual arrangements in force, and calculates the electricity cost in accordance with them. All data managed by the SDMT components must be coded into the SCDF format, which is a file format defined in MERLIN.

This module is made up by the following components:

- Data reading: identifies and loads the relevant information for the cost calculation function (total energy consumption at each SST per period (1hour or 30min), market daily energy price at each SST per period (1hour or 30min), etc.). A specific parser has been developed for this purpose.
- Cost calculation: calculates the energy cost of the defined scenario, taking into account individual contractual arrangements for each SST/PCC consumption.
- Data writing: to update the data file with the optimization results.

2.3 CORE AND USER INTERFACE

This module manages the interfaces and exchange of data among the SDMT modules, the external simulation tools and the user (see Figure 2), effectively providing the “user interface” and “data interfaces” for all the Functionalities provided by the SDMT. More specifically, it has the following functionalities;

- Display the energy consumed, the power peaks and the cost of energy consumed for each investigated configuration (scenario).
- Visualise the trade-off between indicators associated with the four missions.
- Display the parameters describing the calculated configurations, and collect any additional user-defined configurations for the next iteration.
- Write a set of input files for the next iteration, with the objective of analysing the effects of changes to the system design and finding configurations with better performance, as well as ruling out configurations that would violate constraints.

2.4 OPTIMISATION ALGORITHM

This module calculates the parameters to describe new system configurations for the next iteration. Once a set of system configurations has been simulated, the details of these configurations and their performance in relation to the missions (see section 2.1) are sent to the Optimisation Algorithm, which uses this information to generate a set of new possible configurations that target improved system performance using a multi-criteria optimisation.

2.5 DEPENDENCIES

Table 2 shows the interdependencies among the modules of the SDMT. As it has been conceived as a monolithic system, its modules are not intended to be launched separately. Also, it should be noted that the SDMT relies on an external multi train simulator to estimate accurately the energy flows.

Table 2 : Dependencies of the modules of the SDMT

	Operation cost calculation	Core and user interface	Optimisation module	Multitrain simulators (external)
Operation cost calculation		Required	Not required	Required
Core and user interface	Not required		Required	Not required
Optimisation module	Required (*)	Required		Required

(*) Required when the operational cost is used as a mission

2.6 Deployment

The deployment of an SDMT requires the completion of the following tasks:

- Configuration for the optimization variables to be explored.
- Development of the appropriate input-output routines to be able to export/import data to/from the SCDF format defined in MERLIN. Alternatively, translators can be developed to convert the proprietary formats to the SCDF format. These interfaces are necessary to allow the communication between the SDMT and the external multi-train simulators.

To deploy the SDMT the following steps are implemented;

- As noted previously a multi train simulation tool is required.
- Clear objectives should be set chosen by the user with a selection of parameters chosen to optimise.
- Scenarios should be defined. These may include; Type of traffic, Electrification characteristics and layout, Operational regime and procedures, Network/route characteristics and layout including topology and other aspects such as contractual and financial constraints related to energy/power procurement.
- Examples of objective and scenario definition can be found in *(1)*

Following this, the operation procedure for the SDMT can be found in;

- Core and user interface module Annex 01 *(8)*
- Contractual arrangements module Annex 02 *(5)*
- Optimisation Algorithm- Annex 03 *(6)*
- *(7)* SDMT VIDEO TUTORIAL

Partial deployment is possible but would be dependent on the optimisation variables. As needed, additional variables to those already defined can be added.

2.7 Limitations

The aim of the development of the SDMT has been to verify the suitability of the initial architecture defined in the project (WP2). This architecture has been implemented using a modular software tool (SDMT), in order to investigate (WP6) a number of scenarios (WP3) with the primary goal being to test such architecture. The results have corroborated the suitability of using the architecture defined so it can be taken forward as an output of MERLIN.

The description, methodology and objectives of the scenarios were developed to test the architecture using the tools (SMDT and REM-S). This meant that the scenarios have been tailor-made to fulfill this objective. For instance they facilitate establishing the requirements for a SDMT common data format that allows the exchange of data between the different software modules.

Therefore, the SDMT in its current form is limited to the application of strategic decision based on the MERLIN scenarios. Time, budget and scope constraints have meant that while a success, the SDMT lifespan in its current format is limited. Nevertheless, it has proven that Multidisciplinary System Design Optimisation (MSDO) provides the basis for a methodology to a decision support system that can guide the user towards design decisions that improve the objectives targeted (e.g. reduce energy and power consumption while maintaining service levels).

3. RAILWAY ENERGY MANAGEMENT SYSTEM REM-S

3.1 General Description

In order to achieve a more sustainable and optimised energy usage in European electric mainline railway systems, optimisation is performed at different levels, represented by three Operational Modes referred to a temporal schedule: Day Ahead Optimisation (DAO), Minute Ahead Optimisation (MAO) and Real Time Operation (RTO), corresponding to the control and implementation of the actions coming from the optimisation. These operational layers are described in *(2)* and represented in Figure 3.

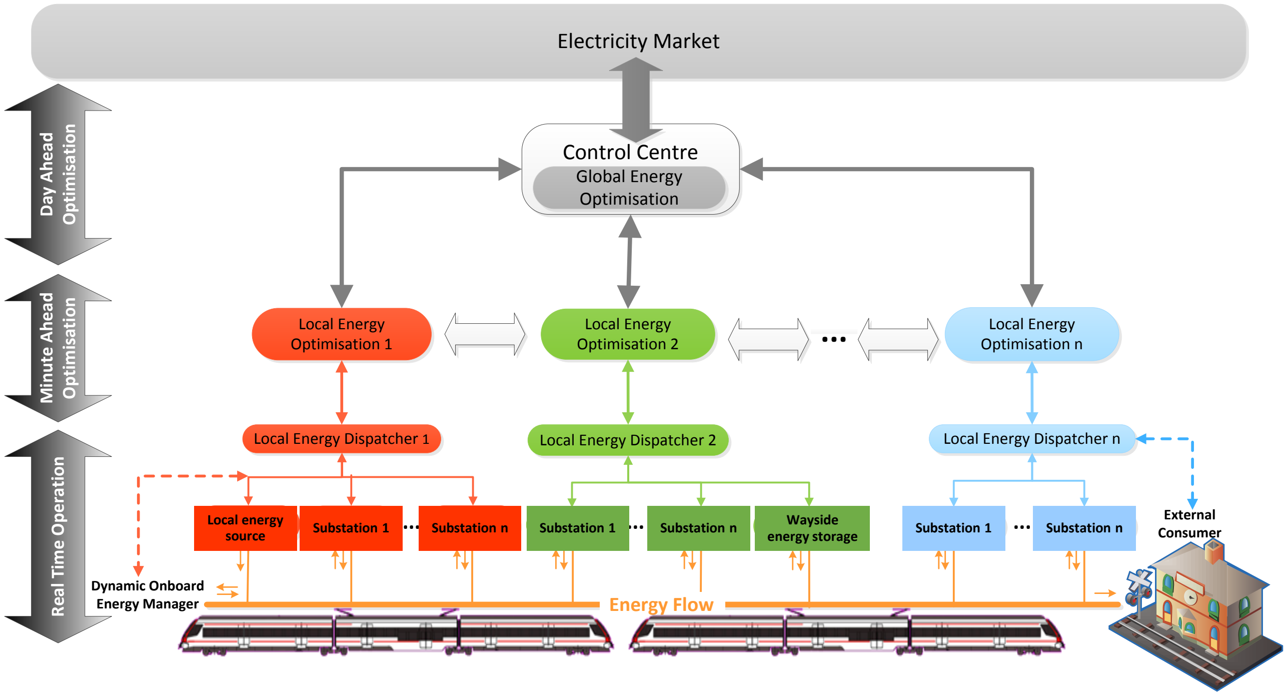

Figure 3 : Schematic representation of the REM-S optimisation concept

Figure 4 represents the functions of these different operational modes and their operation along the timeline.

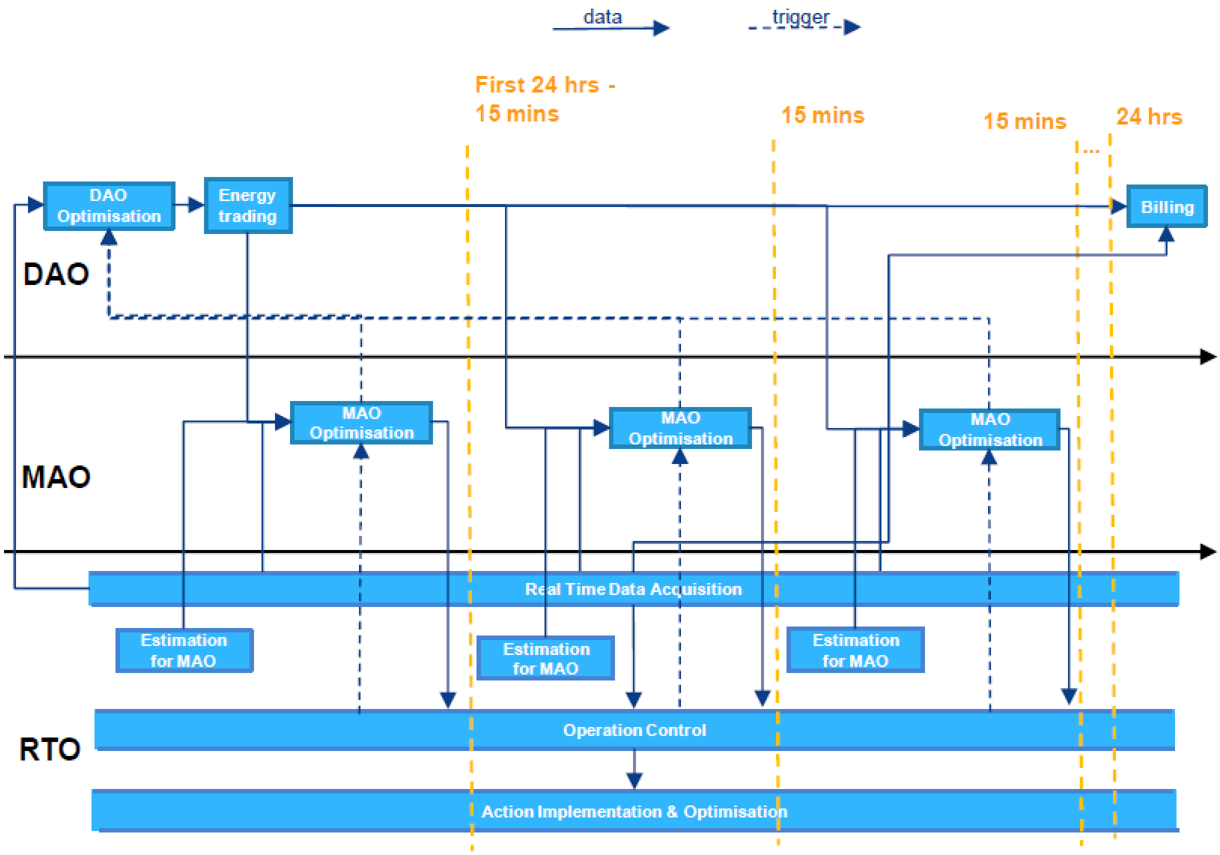

Figure 4 : REM-S Functions and Operational Modes

3.2 Day Ahead Optimisation (DAO)

3.2.1 Description

The main aim of the DAO is to calculate the optimum operation of the network (including trains, ESS, DER, etc.) for the 24/48 hours time horizon and the corresponding energy procurement. The optimisation is usually launched once a day or when a significant deviation is identified (by MAO or by the EBDM). The DAO included three main functionalities:

A) Optimisation of power profile (GOS)

It determines the power and energy consumption of the whole network trying to reduce the peaks of power and the total amount of consumed energy, per point of common coupling, based on the following information:

- Model of the IM electrical network, including the real time status of each piece of equipment.
- Expected timetables for the next day.
- Real time power consumption restrictions for the feeding sections.
- Expected rolling stock compositions.
- Forecasted power profiles of each RU.

- Forecasted power profiles for each DER.
- Estimated average price of the energy consumed by every PCC.
- Price variations from the DAO (needed to decide if a new optimization is needed).

B) Energy trading (EBDM):

It determines the optimal way of purchase the energy (given a portfolio purchasing alternatives, from the sport markets and using contractual arrangements) y the expected average price of the energy related to a given energy demand, based on the following information:

- Forecasted energy demand, in block of a given likelihood.
- Forecast of the electricity spot markets, for each hour and each market session.
- Results of previous sessions of the electricity spot markets
- Constraints derived from the long term contractual arrangements
- Bidding strategies, i.e. criteria to determine the energy blocks and their price for each markets session.
- Additional TSO/DSO/EMO costs

C) Billing:

It calculated the real cost of the consumed energy to be charged to every consumer.

3.2.2 Dependencies

For DAO, responsible for global energy management, the EMS/SCADA (Supervisory Control and Data Acquisition) system is required in order to support operational activities for dispatching energy at higher level of system. Global Optimisation Software (GOS) supports intelligent functions of REM-S in the Control Centre and makes an optimum plan for the next day. It must have a RU server, an IM server and a DER EMS and VPP system to be responsible for gathering the next day forecasting of timetables, power demands and energy generation.

Table 3 shows the internal dependencies among the functions of the Day-Ahead Optimization (DAO), namely: (i) the Global Optimisation of power, energy and price, (ii) the Energy Trading and (iii) the Billing.

Table 3 : Dependencies of the functions of the DAO.

	Optimisation of power, energy and price	Energy trading	Billing	Multitrain simulator
Optimisation of power, energy and price		Not required	Not required	Required
Energy trading	Not required		Not required	Not required
Billing	Not required	Not required		Not required

Although these functions have been developed to work together, it is possible to run them independently (as far as the information coming from the rest of the functions can be obtained elsewhere):

- The Global Optimisation (GOS) determines the operation of the infrastructure (DERs, ESSs, etc.) and the trains (selection of the driving profiles), based on the selected objectives (energy, power or cost minimisations). This optimisation can be carried out regardless of the origin of the energy prices (based on the contractual arrangements or determined by an optimization), but the volatility of the final energy prices may increase significantly.
- The Energy Trading (EBDM) optimizes the energy procurement sources (energy markets and contractual arrangements), for an expected energy demand (which is stochastic) which is an input. However, by itself it is not able to optimize the operation at the Global optimisation does.
- The billing process requires the energy and economic flows, regardless of how these flows were determined (by an optimization of the operation or just following a sensible program).

These functionalities may be deployed separately, provided that an alternative source is established for the information needed by each functions.

3.3 Minutes Ahead Optimisation (MAO)

3.3.1 Description

The main aim of the Minutes Ahead Optimisation (MAO) is to ensure that the operation previously optimised by the DAO is followed, by correcting any deviation that could occur. This optimization is launched every 15 minutes (or a period differently configured) or when there is a deviation between the forecasted and the real behaviour of the system during MAO that cannot be solved by RTO control.

Following the profiles determined by the DAO and the MAO covers the interaction with all local agents to fulfil power restrictions, accommodates surpluses and the needs of the adjacent sub-networks, and accordingly suggests actions to local agents, i.e. TSSs (substations), RTSSs (reversible substations), DERs (Distributed Energy Resources), ESSs (Energy Storage Systems) and the trains passing through the sub-network in the next timeslot, based on the following information:

- Aggregated 15-minutes power profiles, produced by the RTO.
- Power profile required for each hour, at each PCC.
- Real time status of the network.
- Power profiled needed by each RU.
- Real time restriction that may arise during operation, such as power limitations.

3.3.2 Dependencies

Because of its nature, the whole set of features of the MAO has to be implemented to work properly.

3.4 Real Time Operation (RTO)

3.4.1 Description

The main aim of the Real Time Operation application is to fulfil the optimal power profiles that were previously calculated by the MAO for the sub-network, taking into account: (i) the real time status and behaviour of all controllable components of the sub-network and (ii) surpluses and needs of the adjacent sub-networks. To do so, it suggests adjustments to those sub-network pieces of equipment which have the ability to influence the network instantaneously, such as ESS or SST settings. It should be noted that the optimisation process covers only network static equipment, as the trains are not able to react immediately and their management is too complicated to be predicted.

In addition, the RTO estimates the behaviour of the DOEMs, DERs and external consumers for the next 15 minutes or the remaining of 15 minutes for the MAO operational mode.

3.4.2 Dependencies

Table 4 shows the internal dependencies among the functions of the Real-Time Operation (RTO), namely: (i) Optimisation of the energy and power flows, (ii) Estimation for MAO, (iii) the Operation Control and (iv) Implementation of Control suggestions.

Table 4 : Dependencies of the functions of the RTO

	Real time data acquisition	Estimation for MAO	Operation control	Implementation of control suggestions	Multitrain simulator
Real time data acquisition		Not required	Not required	Not required	Not required
Estimation for MAO	Required		Not required	Not required	Not required
Operation control	Required	Required		Not required	Not required
Implementation of control suggestions	Required	Not required	Required		Not required

Because of its nature, the whole set of features of the RTO has to be implemented to work properly.

3.5 Dependencies

Table 5 shows the interdependencies among the sub-systems of the REM-S, namely the Day-Ahead Optimization (DAO), the Minutes-Ahead Optimization (MAO) and Real-Time Operation (RTO).

Table 5 : Dependencies of the functions in the REM-S

	DAO	MAO	RTO	Multitrain simulator (external)	Single train simulator (external)
DAO		Not required (*)	Not required	Required	Not required
MAO	Not required		Required	Required	Not required
RTO	Not required	Required		Not required	Required

(*) Although DAO is able to optimise the operation for the whole day, the driving assistance system (DAS) would not be available if the MAO is not implemented

Although the sub-systems are intended to work together, it is possible to run them independently but it may be ill advised as each of them solves a part of the problem (optimality, robustness, etc.):

- The DAO provides an optimal operation plan for 24/48 hours horizon. However, it is not suitable when deviations occur in real time (delays, congestions, etc.) because of its computational load.
- The MAO manages the deviations that occur minutes ahead so that the operation plan determined by the DAO is recovered. The MAO does not produce a global optimum (in some cases, not even a local optimum), but it corrects the deviations from the global optimum as they occur. A key part of the MAO is the DOEM, the driving optimization module which also manages all the power consumptions on-board (traction and other loads) and is in charge of the execution of the instructions received from the smart grid. For that reason, the MAO is the only subsystem able to ensure a train follows a power profile.
- The RTO manages the deviations that occur seconds ahead so that the operation plan obtained by the DAO and the MAO is recovered. The RTO does not produce an optimum, but it corrects the deviations as far as this is possible.

A partial implementation of the REM-S can be foreseen. This includes, for example, the deployment of a sole LOS on part of the network (to govern one or several substations), having the DOEM on-board a limited number of trains serving the concerned routes. A following step could be the extension of the DOEM on the whole fleet, thus having the complete control of that part of the railway network.

The advantage of having a partial implementation of the REM-S is the reduction of costs, as for example, not equipping the whole fleet with DOEM led to a lower investment and installation cost.

3.6 DEPLOYMENT

The modules of REM-S are independent; for this reason a partial deployment is possible. The following figure (Figure 5) describes graphically the main phases of REM-S deployment.

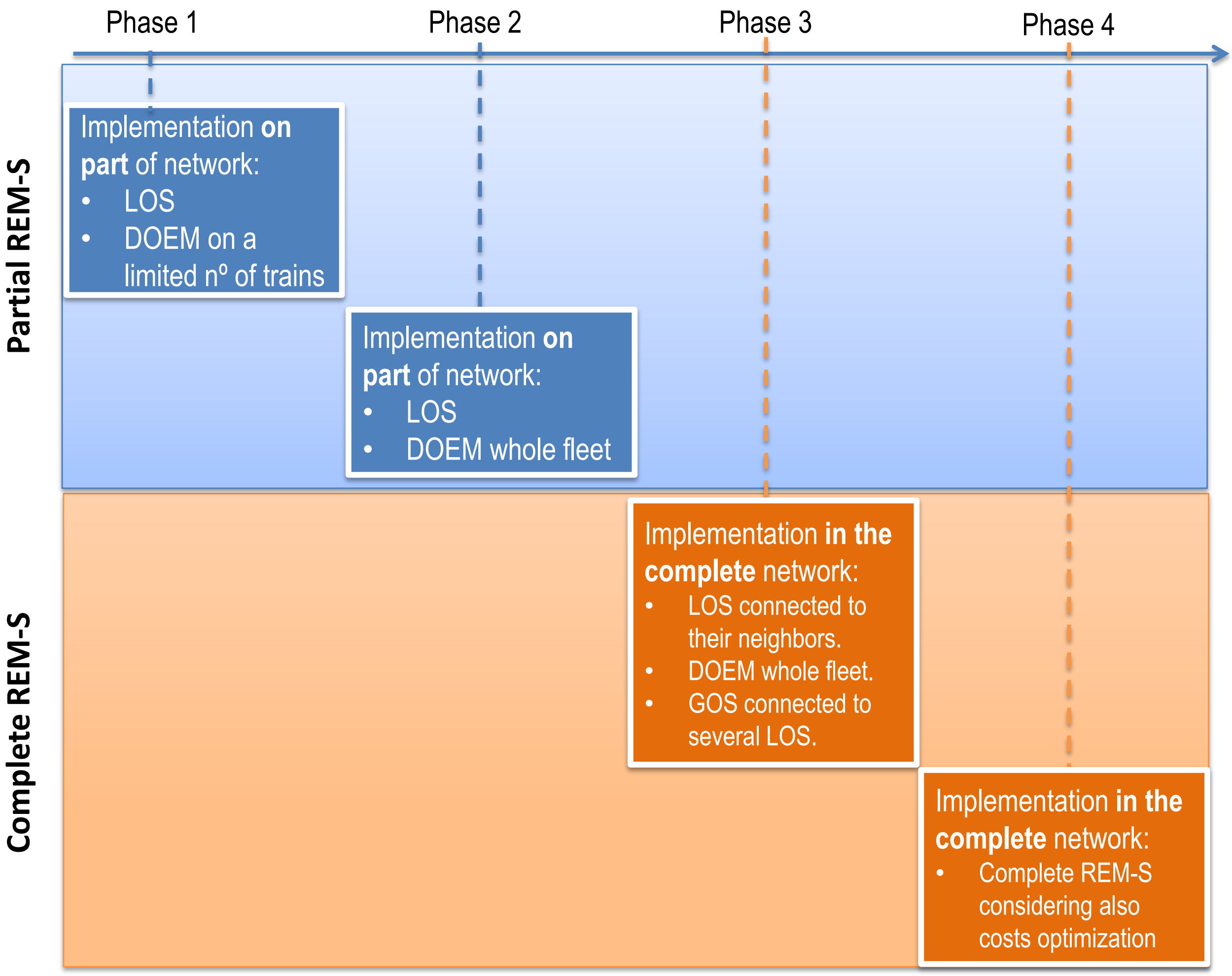

Figure 5 : REM-S deployment

The main phases of REM-S deployment are described in the following:

1. Partial REM-S deployment: local optimisation on part of network.

The basic deployment of the REM-S is obtained only with LOS and implementation of the DOEM on a limited number of trains (of a limited number of RU) and areas of the network. This solution provides a limited flexibility, as many grey trains, not included in the optimisation process, exist. Moreover the optimisation is constrained to those parts of the global network and to the MAO function. Alternatively to the DOEM, ESS, DER or EC can be present or gradually included in the optimisation process (i.e. implementation of the RTO function), given that one of them provides controllability.

2. Partial REM-S deployment: local optimisation of the whole fleet within a region.

A partial deployment of REM-S is obtained only with LOS and implementation of the DOEM on the whole fleets (i.e. all train of all RU) in certain areas of the network. In this way, every element of the network is controllable.

3. Complete REM-S: energy and power optimisation within a region.

Taking into account only energy and power optimisation as missions, REM-S is implemented through the Energy Dispatcher (GOS and LOS) in the complete network, considering whole fleets equipped with DOEM. In this case, DAO function is additionally implemented and GOS is connected to the several LOS, and each LOS with their neighbours.

4. Complete REM-S: energy, power and cost optimisation

This is the most complete level of REM-S deployment, consisting in the use of the whole REM-S and taking into account also cost optimisation.

This solution foresees the use of complete Energy Dispatcher (GOS and LOS), EBDM and DOEM for the whole fleet. This considers the three missions of REM-S and allows complete optimisation at network level.

3.7 Limitations

MERLIN proposes the architecture of the rail smart grid. This architecture, including functions, main components and interfaces, has been designed to be modular and scalable. It must be noted that on top of such architecture the optimisation algorithms must be designed and implemented.

Indeed, experience shows that there is no universal optimising algorithm as each case or scenario has its own particularities, business cases and targets. Thus, the deployment of the various REM-S modules requires the design, implementation and testing of customised optimisation algorithms.

Although the DOEM has been conceived as a function rather than a device, it may be the case that it cannot be integrated in existing onboard computers when the train is retrofitted to be compliant with the REM-S. The DOEM implements a train simulator which could be more or less complex and consequently more or less accurate, but that requires in any case certain processing capacity, which could not be available in old or busy computers. In that case additional suitable hardware must be installed.

The REM-S relies on stable and almost permanent communication links amongst the agents, including trains, substations, railway undertakings' operation dependencies, traffic control centres, etc. Any infrastructure manager interested in deploying the proposed rail smart grid should invest firstly in communications.

Concerning performance of the REM-S it strongly depends on the available flexibility of the network. The flexibility can be provided by any of the agents but mainly by the trains and by controllable components of the power distribution chain (e.g. ESS, reversible substations, (un)pluggable loads…).

However, regardless the potential benefits of the REM-S in terms of energy and power consumption reduction, it is a fact that any investment is made in base of a supporting business case. In that sense, regional, national or even European councils should enforce the establishment of fair rules concerning energy sent back to the public network and in general, the role of railways as an active actor of any country energy map.

4. LESSONS LEARNT FOR THE IMPLEMENTATION

Based on the work carried out in project MERLIN and especially the experience acquired in the scenario analyses, the following learnt lessons related to the implementation can be highlighted:

- The optimization processes envisioned need the decision variables and the constraints to have some clearance (called “flexibility” in the context of the project MERLIN) to achieve better results. In cases where a minimal flexibility in the driving profile is available without unacceptable delays and impacts on other services (see conclusions of scenario 5: Penrith to Euxton Junction Line), there is very little room for improvements.
- The volume of new information flows are significantly larger than in traditional electrified railways and for that reason, their practical implementation is also one of the big technical challenges to be faced (especially, in railways with insufficient communication capacities) to implement the REM-S. However, mobile communication coverage is not always as good as required, which may be a serious limitation for some lines. For that reason, it would be advisable to develop asynchronous communication schemes more robust in intermittent coverage situation.
- In the MERLIN project, a general architecture for a railway smart grid has been defined. It should be noted that the specific details of each practical implementation may differ. For instance, the criteria to define the zones in AC 50Hz systems (with neutral zones acting as natural separations between sections) will be different from DC or AC 16,6Hz. However the architecture has proven to be general enough to cover the existing cases.
- The time horizons used in DAO and MAO are strongly coupled to those already existing in the day ahead and intraday electricity spot markets. Therefore, the specific values used in each case must be adapted to the actual needs. For instance, while in Spain the energy is traded for each hour, in UK it is for each 30 minutes.
- Although the interactions between railways and the electricity markets have been considered (day ahead and intraday energy spot markets) in the project MERLIN, further advances should be pursued in future research projects, especially to allow railway to provide ancillary services to the electrical system operator which delivers a higher added value than regular energy.
- The installation of energy meters both on board and in the infrastructure is crucial to assess the efficiency of the optimization procedures described in MERLIN. In addition, it will provide valuable information to be exploited for further improvements in the operation.
  In accordance to Directive 2009/72/EC, a huge effort has been devoted in the last years to conceive and develop the smart metering equipment and protocols.

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