Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 00 (2022) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

Transport Research Arena (TRA) Conference

DAYDREAMS - Development of Prescriptive Analytics based on Artificial Intelligence for Railways Intelligent Asset Management Systems

L Oneto[a], M Anastasopoulos[b], D Anguita[a], I Baroni[c], R Canepa[d], C Dambra[e], S Gogos[f]*, W Jentner[g], S Petralli[d]

[a]*University of Genoa, 11A Via Opera Pia, Genova 16145, Italy*
[b]*Institute of Accelerating Systems and Applications, P.O. Box 17214, Athens 10024, Greece*
[c]*CEFRIEL, 226 Viale Sarca, Milan 20126, Italy*
[d]*RFI - Technical Department, 6/5 Via Don Vincenzo Minetti, Genova 16126, Italy*
[e]*ZenaByte, 2 Via Cesarea, Genova 16121, Italy*
[f]*UNIFE, 221 Avenue Louise, Brussels 1050, Belgium*
[g]*University of Konstanz, 10 Universitätsstr., Konstanz 78464, Germany*

Abstract

DAYDREAMS, which started its activities in December 2020, is a Horizon2020 project within Shift2Rail's 3rd Innovation Programme (IP3). The project's overall objective is to advance - in line with Shift2Rail's vision (now called Europe's Rail Join Undertaking) - on the integration and use of data and artificial/human trustworthy intelligence, together with context-driven Human Machine Interface (HMI) for prescriptive Intelligent Asset Management Systems (IAMS) in railway.

Keywords: Railway; Asset Maintenance; Artificial Intelligence; Prescriptive Analytics; Multi Objective Optimisation; Context Driven Human Machine Interface.

* Corresponding author. Tel.: +32-476-666-5081;
E-mail address: stefanos.gogos@unife.org

1. Overview and motivation

According to the International Union of Railways the length of tracks maintained by the European railway sector exceeds 300.000 km operating more than 5 billion train-kilometres and offering services for more than 400 billion passenger-kilometres. A steady increase is expected for the next 30 years making railways a key-asset in the European transportation ecosystem. Although European Railways remain the safest in the world, according to data reported in 2017 by the EU Agency for Railways, there have been on average just over 2.000 significant accidents each year on the railways of the EU Member States. The economic impact of these accidents has been estimated in the order of EUR 1.61 billion for 2015.

To address railway safety challenges, United Nations Member States agreed on a set of measures promoting sustainable development ensuring access to safe, affordable, accessible and sustainable transport systems for all citizens by 2030. Besides the United Nations, the European Commission also released a new European Mobility Package setting a target for zero traffic fatalities and severe injuries by 2050. To achieve these goals, enhancement of the existing asset management decision support systems with advanced data analytics and mathematical modelling tools is expected to play a key role. These tools can be used not only to predict future issues but also to provide solutions for preventing and solving them, proposing actions to enhance safety, availability and reliability and reducing maintenance costs.

The European Shift2Rail Joint Undertaking has established in its Multi Annual Action Plan that for "delivering the capabilities to bring about the most sustainable, cost-efficient, high-performing, time-driven, digital and competitive customer-driven transport mode for Europe" among other characteristics, intelligent maintenance should be introduced to increase capacity and availability and to reduce maintenance costs. The Shift2Rail Joint Undertaking also identifies, among the key enabling technologies, machine learning, artificial intelligence and big data analytics targeting predictive and possibly prescriptive maintenance in Shift2Rail demonstrators: Dynamic Railway Information Management System, Intelligent Asset Management Strategies, and Business Analytics Platform.

1.1. Project scope and structure

DAYDREAMS will advance on the integration and use of data and artificial/human trustworthy intelligence, together with context-driven HMI for prescriptive IAMS in the railway by:

- Advancing the maintenance approach by moving from preventive and predictive asset management towards prescriptive asset management.
- Largely improving the decision-making process by developing multi-objective decision optimisation approaches that take into account all possible, and often conflicting, implications of IAMS decisions in the railway environment (e.g., on Traffic Management System, Energy, Freight, etc.,).
- Reinforcing the role of the person-in-the-loop by designing and developing advanced context-driven HMIs to allow context- and risk-aware multiple-options decision-making processes supported by the information on data sensitivity and robustness. The HMI will allow the person-in-the-loop to:
    - Properly access and visualise predictions/metrics and models;
    - Assess why and how the model predicts something ("opening the black-box");
    - Steer models by setting parameters;
    - Evaluate alternatives using parameter steering and extend this process through speculative execution.

While previous projects involving DAYDREAMS partners, such as **IN2RAIL** and **IN2DREAMS**, have successfully addressed condition-based and predictive maintenance approaches that improved traditional reactive and preventive maintenance methodologies, DAYDREAMS will exploit state-of-the-art technologies to tackle complexity and exploit the business value of prescriptive approaches already used in other industrial fields. DAYDREAMS will also increase trust by utilising blockchain and smart technologies inherited from IN2DREAMS to track and monitor the IAMS adoption and use in multi actors' environments.

DAYDREAMS will reach its objectives through the design, development, and integration of three technological pillars:

- **AI and Machine Learning** for asset management prescriptions based on asset status nowcasting and forecasting. These technologies will be targeted to model the entire maintenance process, through the use of both endogenous and exogenous (e.g., environmental) data, including asset-related physical models of the phenomena and human behaviour/decisions/actions, which holistically describe or affect the asset management process;
- **Multi-objective Optimisation** (including AI- and stochastic-based methods). These technologies will be targeted to prescribe optimal decisions to railway stakeholders, by ranking a list of possible options, together with related risks and uncertainties, taking into account both stakeholders' and maintenance process metrics and constraints, taking into account stakeholders' KPIs, preferences, and constraints.
- **Context-driven HMI**. These technologies will allow improving the effectiveness of information transfer (e.g. prescribed action with associated KPIs and uncertainties) to decision-makers and will allow the collection of stakeholders' behaviour, as to obtain an effective risk-aware human-in-the-loop integrated system.

The project is therefore structured into seven different Work Packages (WPs), where WP2, WP3 and WP4 will cover the main technological pillars (AI, MOPs and context-driven HMI) that are described above, while WP5 and WP6 will cover the implementation of the IAMS Prototype and its evaluation and validation, respectively.

The figure below illustrates how the project is organised:

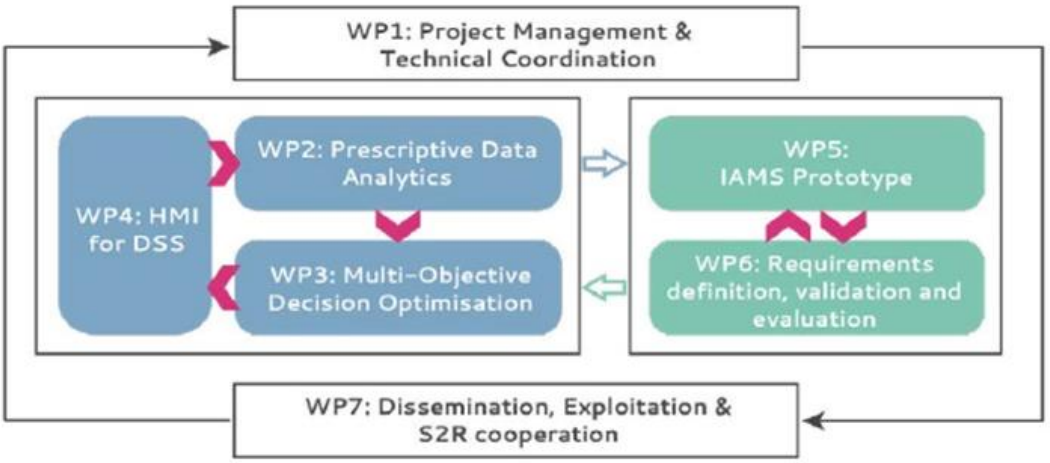

Fig. 1. DAYDREAMS project structure.

2. Prescriptive Data Analytics

Previous and current approaches to railway asset maintenance have successfully addressed condition-based and predictive maintenance approaches, improving traditional reactive and preventive maintenance methodologies. DAYDREAMS will design and develop state-of-the-art AI-based technologies to tackle the complexity and to exploit the business value of the prescriptive approaches already showing up in several industrial fields.

The prescriptive approach is not only able to answer questions like “What is happening?” (the condition- based approach), or “What will happen?” (the predictive approach), but it can provide answers to questions like “What could be done?” and “What are the best options?” optimising - under context specific asset management constraints - preferences and KPIs of railway stakeholders (see Figure 2).

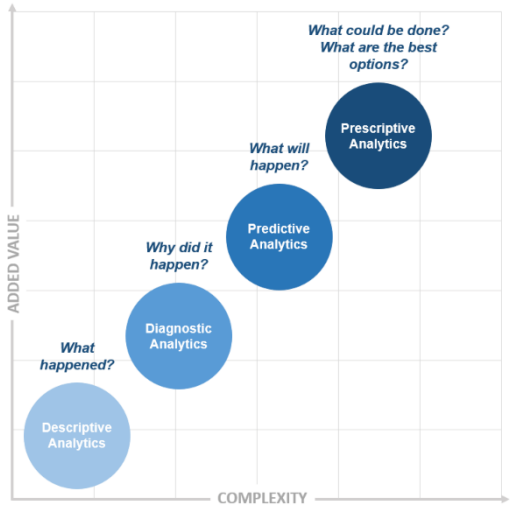

Fig. 2. From Condition-based and Predictive Maintenance to Prescriptive Maintenance.

The first step performed in this direction was to review the state of the art in prescriptive maintenance. Then four different scenarios have been developed:

- Scenario 1 (from Hitachi Rail, partner of the IN2SMART2 CFM Project): Management of Track Circuits (TC) in a Metro Environment.
- Scenario 2 (From Rete Ferroviaria Italiana, DAYDREAMS partner): Railway Infrastructure Maintenance Management in RFI.
- Scenario 3 (From Stimio, DAYDREAMS partner): Joint optimisation of Train Traffic Scheduling and Maintenance Planning.
- Scenario 4 (From TrainOSE, DAYDREAMS partner): Joint optimisation of track maintenance planning and multi-modal trans-port for service continuity.

For all scenarios:

- a detailed description has been provided together with the specific user requirements,
- then the state of the art on the specific solutions has been reviewed to pave the road for a prescriptive solution to the problem, and finally
- the metrics to evaluate the quality of the solution have been defined.

In the meantime, data for the implementation have collected and implementation has been started and is currently ongoing according to the pipeline shown in **Error! Reference source not found.**. Scenarios 1 and 2 will rely on predictive (ML-based predictive model) and prescriptive (AI-based planning and scheduling tools) analytics. Instead, Scenarios 3 and 4 will focus on predictive analytics that will be exploited for Multi-Objective Decision Optimisation.

3. Multi-Objective Decision Optimisation

This activity focuses on the development of technology solutions that can be used to identify optimal maintenance plans ensuring cost-effective operation of the railway network. This is a challenging problem as decisions to perform specific maintenance activities may lead to service disruptions. The problem is further exaggerated especially in railway networks comprising double-track lines without redundancy where maintenance affects not only service

availability and reliability but also safety. In such systems, service continuity is commonly achieved through the deployment of an alternative transportation service interconnecting segments of the railway network that is under reconstruction/repair. A typical example includes the "TRAINOSE Bus service" that has been introduced by TRAINOSE as an alternative transportation option to interconnect parts of the railway network that are out of operation.

However, the majority of the existing approaches treat the problem of optimal railway track maintenance and multi-modal transport deployment for service continuity separately resulting in increased operational costs and reduced comfort for passengers. In response to this, Multi-Objective Optimization (MOO) decision making can be applied to identify a set of strategies that can minimise:

- possession and maintenance costs affecting both rail infrastructure managers and rolling stock providers.
- delays that occur either from a possible deterioration of track quality or a failure to accurately estimate the time needed to complete the set of maintenance activities needed.
- service disruption through consideration of complementary transportation options for passengers.

To effectively solve this type of problems, monitoring solutions providing real-time continuous survey of the track defects (position, type, evolution) are needed. These are very valuable for maintainers to anticipate repair work and reduce manual inspection that is often performed at night. If failures that occur are not monitored, they could lead to rail breakdown causing traffic interruption. At the same time, it is very costly for maintainers to have people visiting the field in order to carry out this operation, especially when it requires traffic interruption (possession).

Fig. 3. Sensors installed by STIMIO.

Towards this direction, during the first period of the project a set of fully automated solutions that can monitor the status of the tracks have been deployed by STIMIO and TRAINOSE. Sensors monitoring a variety of parameters (such as acceleration, vibration, position etc) have been attached to the rolling stock frame, continuously monitoring the status of the tracks.

Based on the collected datasets, Machine Learning (ML) schemes able to detect track defects and estimate the deterioration rate of track quality over time have been developed. The output of these models has been used as input to a set of MOO problems that have been formulated in order to estimate the candidate time periods during which maintenance activities can be scheduled under various constraints and cost functions. The constraints and cost functions were carefully selected to reflect the requirements of the stakeholders involved in the decision-making process.

Emphasis was also given on the development of AI-based optimization methods, that can improve classical algorithms and guide the optimiser toward regions characterised by reasonable trade-offs between computational time and optimality. To achieve this, a set of novel AI models purposely designed to support the TRAINOSE, STIMIO and RFI use cases has been provided. These models include:

a) a Neural Network model based on the Kennedy-Chua NN able to solve the multi-objective / multi-modal service continuity problem.

b) a set of Neural Network models based on the Hopefield and Tank-Hopefield models that can prioritize maintenance actions and assign these policies to the appropriate teams
c) a Genetic Algorithm solving the multi-asset / multi-objective / multi-maintenance team scheduling problem.

4. Context-driven HMI

This work package builds upon the results work WP2 and WP3 which provide artificial intelligence and multi objective optimisation models. Here, these models are to be combined with human-machine-interfaces (HMIs) to empower the user to gain deep insights into the models as well as steer them to optimise decision making processes.

The HMI integration with the models shall allow the user:

- to immediately and transparently access the results of the models as well as their uncertainties to support the decision-making process
- to steer the models and change the overall context to answer "What if …?" questions
- to access the models in a detailed manner such that the decision-making process of the model becomes transparent to the user (explainable AI)
- to input expert domain knowledge to foster a symbiosis between the human and the mcahine (visual analytics)

The work in this work-package began by conducting a throughout survey of the state-of-the-art in research and industry regarding HMIs for asset management followed by a specific survey of the current state-of-the-art at the stakeholders' premises. The sought achievements for DAYDREAMS wil increase this state-of-the-art significantly with prescriptive analytics, explainable AI, as well as, visual analytics to encompass the human-in-the-loop.

Throughout the first year, an intensive exchange with stakeholders has been conducted to gather requirements and stakeholder specific details about the data. Furthermore, with partners of the other work packages (WP2, WP3, WP5, WP6), interfaces for the models, data, and user interactions have been defined plus an initial system of the WP4 prototype has been created. The initial prototype is already capable of bein integrated into the system developed in WP5 and thus bootstraps all ongoing research and development activities.

Interactive mockups for the Scenario 1 (IN2SMART2 - HITACHI): Management of Track Circuits in a Subway Environment and Scenario 2 (RFI): Railway Infrastructure Maintenance Management in RFI have been implemented into the prototype and will soon be connected to the first versions of machine learning models that are currently being trained. The interactive mockups for the remaining two scenarios (Scenario 3 (STIMIO) - Joint optimisation of Train Traffic Scheduling and maintenance planning & Scenario 4 (TRAINOSE) - Joint optimisation of track maintenance planning and multi-modal transport for service continuity) are in active development.

With the current state of the prototype we can quickly develop and iterate new versions and include the stakeholders' feedback early-on.

5. IAMS Prototype

The IAMS prototype will integrate prescriptive analytics, multi-objective decision optimisation and context-driven HMI software implementations, demonstrating their effectiveness in four different use cases. The IAMS prototype, which is currently being implemented, will support the following macro functionalities:

- implement a shared catalogue of reusable digital artifacts allowing different stakeholders to add, describe, update and navigate them according to specific artifact lifecycles;
- offer a runtime environment integrating digital artifacts that implement processes for an intelligent maintenance scenario;
- monitor and track the usage of digital artifacts and the execution of processes related to intelligent maintenance scenarios.

The IAMS shared catalogue represents the pivotal component of the designed IAMS architecture. We envisioned the shared catalogue as the interface for both stakeholders and software components interacting with the digital artifacts integrated through the IAMS prototype. The shared catalogue will support the different digital artifact types identified for DAYDREAMS allowing users to describe them through relevant metadata and offering a set of custom functionalities considering the requirements identified for each artifact type.

The IAMS prototype will also provide a runtime area for the deployment of software components associated with a specific use case scenario (named “Intelligent Maintenance Package”) and functionalities to integrate the associated digital artifacts at runtime.

To foster reproducibility of performed intelligent asset maintenance activities we want to facilitate the reuse by different stakeholders of digital artifacts allowing them to retrieve reproducible descriptions of their past usage. On the other hand, to give stakeholders the possibility of performing a trusted auditing over the usage of the IAMS, we want to provide a trusted way to retrieve and investigate the contextual information describing how a prediction, prescription or plan was generated through the IAMS. To support such requirements, we designed the IAMS Process Tracking module, which will log on a distributed ledger the lifecycle of digital artifacts and triggering of specific APIs exposed by the deployed software components.

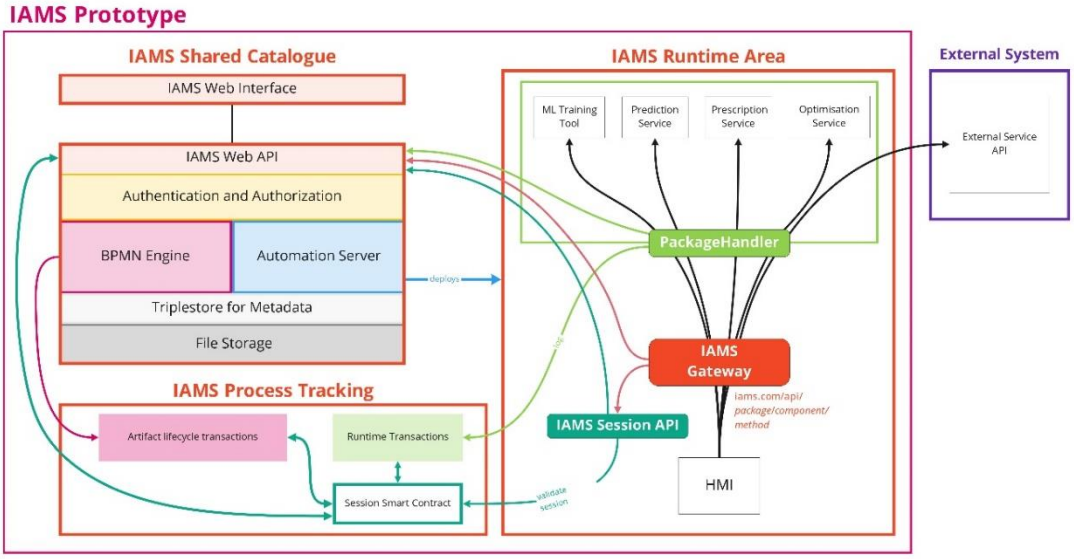

Fig. 4. IAMS Prototype Architecture.

6. Requirements definition, validation and evaluation

The objectives of this transversal work-package are to support the project in evaluating and validating the TRL4 and TRL5 prototypes and how to exploit DAYDREAMS results after the end of the project.

Therefore, the detailed objectives are:

- to define the criteria, metrics, and the related KPIs for the evaluation of the TRL 5 IAMS prototype and its validation on the selected scenarios,
- to assess the sensitivity and robustness of the IAMS prototype,
- to evaluate the IAMS prototype implementation,
- to validate the TRL 5 IAMS prototype on the identified scenarios, and finally
- to define the way forward for industrial exploitation of the TRL 5 IAMS prototype.

The work performed in the framework of the first year of DAYDREAMS, implemented through a continuous interaction with the involved stakeholders, has led to the definition of the criteria to assess, evaluate, and validate the four scenarios of the DAYDREAMS project (in line with the prescription of the ISO 55000 standard).

The adopted methodology consisted of first analysing the elicited requirements of the four selected Scenarios and then identifying the functional and quantitative requirements. The former will be validated through the use of questionnaires (to be finalised when the prototypes and their interfaces will be more mature according to the visual analytics model shown in **Error! Reference source not found.**) while the latter will be validated through KPIs and related target values and baselines.

The analysis has led to the identification of fifteen quantitative requirements out of more than forty overall, and, for each quantitative requirement, one or more Key Performance Indicators (KPIs) and the related target values and baselines have been defined.

All involved scenarios have defined their metrics and related KPIs to be reached both at the end of the DAYDREAMS project and - if results are convincing - when the system will be fully engineered (at TRL9) on the whole network.

The work done constitutes a sound and convincing basis for launching the evaluation and validation activities that will:

- prepare the questionnaires for validating the functional requirements,
- refine KPIs and related target values on the basis of the maturity of each involved prototype,
- implement the TRL 5 IAMS prototype evaluation,
- evaluate the IAMS prototype, and
- validate the IAMS prototype in each scenario.

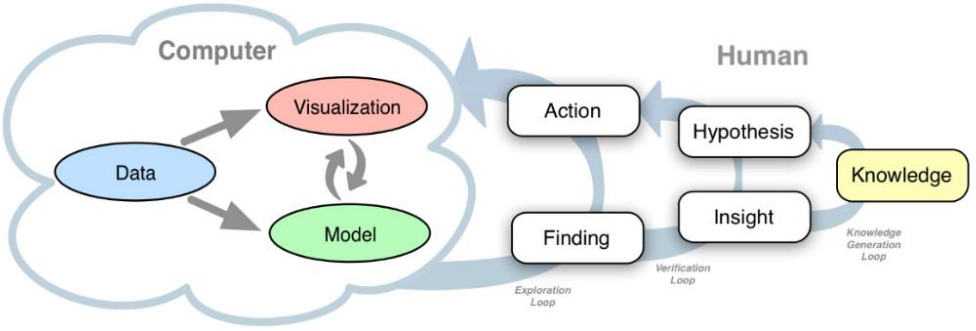

Fig. 5. The knowledge generation model for visual analytics[1].

Acknowledgements

The authors would like to thank the project partners for the work carried out in DAYDREAMS. These are: Cefriel, IASA, RFI, RINA, Stimio, TrainOSE, UNIFE, University of Bristol, University of Konstanz, University of Genova, ZenaByte.

This project has received funding from the Shift2Rail Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008913.

References

[1]D. Sacha, A. Stoffel, F. Stoffel, B. C. Kwon, G. P. Ellis and D. A. Keim, "Knowledge Generation Model for Visual Analytics," *IEEE Transactions on Visualizations and Computer Graphics*, pp. 1604-1613, 2012