Rail4Future

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Report Procedures eliminating complexity (M24)

TLP gelb (Adressatenkreis)

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Deliverable released

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1 Executive Summary

In order to build a large-scale computation platform which enables simulation as a service, performance is a key feature. In this project, mathematical functions, methods combining AI and analytical methods required for fast computing, but credible large-scale simulations are being researched and developed to make the R4F Platform viable for usage. Since this topic consists of different layers in the system, we gather the different approaches from the different layers of simulation deployment and execution in this report. The layers we have to look at are:

- Orchestration, Deployment and Execution.
- Standardization of simulations units.
- Model reduction and simplification methodologies including
  - Classical approaches
  - AI methods.
- Visualization.

These Discussions (and thereby the actual report) can be found in Section 6 of this document.

2 Table of Content

3 Abbreviations and Acronyms

Abkürzungen / Akronyme	Beschreibung
DevOps	Development Operations: Practices, Tools and Procedures for Continuous Development cycles.
FMI	Functional Mock Up Interface
FMU	Functional Mock Up Unit
DT	Digital Twin
MBD	Multibody Dynamics
XML	Extensible Markup Language
JSON	JavaScript Object Notation
MBS	Multibody Simulation
SSP	System Structure and Parameterization
VTI	Vehicle Track Interaction
ML	Machine Learning
R4F	Rail for Future (Rail4Future)
AI	Artificial Intelligence

4 Problem Description

In order to build a large-scale computation platform which enables simulation as a service, performance is a key feature. Simulations can take hours or even days or weeks depending on the complexity of the underlying problem. To make the platform as a service viable it is crucial to reduce the complexity by several magnitudes.
In this project, mathematical functions, methods combining AI and analytical methods required for fast computing, but credible large-scale simulations are being researched and developed to make the R4F Platform viable for day-to-day usage. Since this topic consists of different layers in the system, we gather the different approaches from the different layers of simulation deployment and execution in this report. The layers we have to look at are:

- Orchestration, Deployment and Execution.
- Standardization of simulations units.
- Model reduction and simplification methodologies including
    - Classical approaches
    - AI methods.
- Visualization.

The methods we explore are described in more detail in the following sections.

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5 Impact on the Project

In order to make the application of a large landscape of tools/simulations and large-scale (co-)simulations possible, the models that are provided must be fast and efficient, and the infrastructure must be standardized and as easy to automate as possible. To achieve this goal, a wide variety of techniques from different areas must be applied. This comprehensive report has been compiled to summarize and adequately document the available and newly developed methods during the project.

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6 Description

The actual report is contained within this section. The following points will be discussed:

- Orchestration, Deployment and Execution.
- Standardization of simulation units.
- Model reduction and simplification methodologies including
    - Classical approaches
    - AI methods.
- Visualization.

6.1 Orchestration, Deployment and Execution

To manage a big pool of simulations it is important that they can be deployed seamlessly so that a user can focus on the actual simulation task. However, simulations add a layer of complexity contrary to regular software development as they

a) have a lot data to exchange through the correct inputs and outputs

b) They often need very specialized software which causes a non-uniform tool landscape.

In order to tackle those challenges a graph-based approach is used which was proposed in [2][3]. The concept is based on the so-called Co-Simulation Process Graph which is a combination of process graphs and simulation graphs.

The platform incorporates this concept and leverages co-simulation process graphs and services to store, document, exchange and combine workflows which are used to automatically deploy and execute these (co-)simulations. The codes which are used to run them are generated with help of the graphs. The process graphs themselves are stored within a dedicated graph database so that they can be archived, versioned, viewed and reused at any time.

6.2 Standardization of Simulation Units

There are several different railway assets, containing simulation models and data, which are to be adapted to the R4F Platform by making them even more tool-independent, portable as a container and co-simulative while describing and exchanging their parameters with each other. First, the Functional Mockup Interface (FMI) maintained as a Modelica Association project is preferred to be used for the adaptation process of the models because we found the free interface standard quite promising to build an interface between different dynamic simulation models incl. the railway models we use and their default tools. With this technology we can distribute the models with their belonging data as a container in ZIP format consisting of a XML model description file, binaries and C-code, and the interface standard is already supported by more than 200 tools. The simulation unit of the standard is called Functional Mockup Unit (FMU), which is the ZIP file including the simulation model and its belonging data. (https://fmi-standard.org/)

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The second interface standard we preferred to use is the System Structure and Parameterization (SSP) standard, which belongs to the Modelica Association as well. This standard defines complete systems consisting of one or more FMUs, which co-simulate together and represent different railway models with their data in our case. Besides the technology helps to encapsulate all the FMUs in a ZIP container, which is an important step to keep and then ensure the entire intellectual property of the railway assets while describing and exchanging parameters between the FMU models in the container. (https://ssp-standard.org/)

Fig. 1a shows the typical approach to standardize the simulation units of all the railway models to be integrated into the R4F Platform. Fig. 1b shows the generalized simulation approach, where a simulation code script is implemented to bring the SSP and FMI standardized models with their belonging additional input datasets into an FMI-based simulation and generate simulation outputs as JSON at the end in the platform. (see Kugu et.al. [1] for further information)

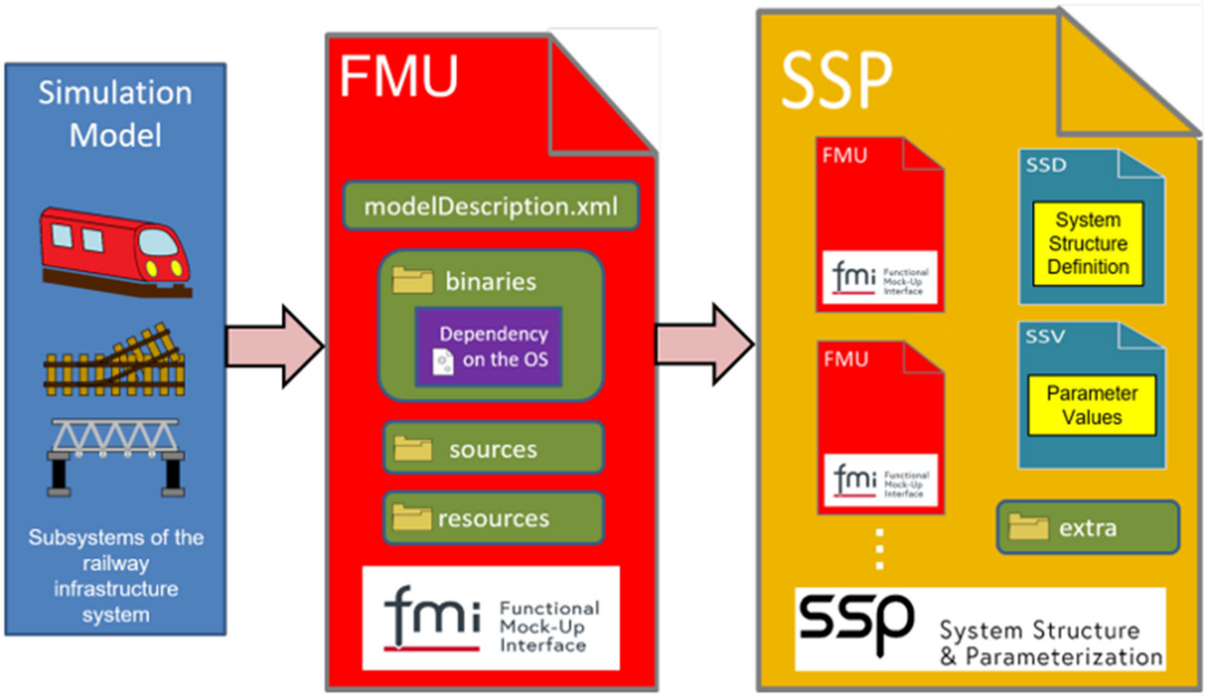

Fig. 1a) Model Standardization Approach. [1]

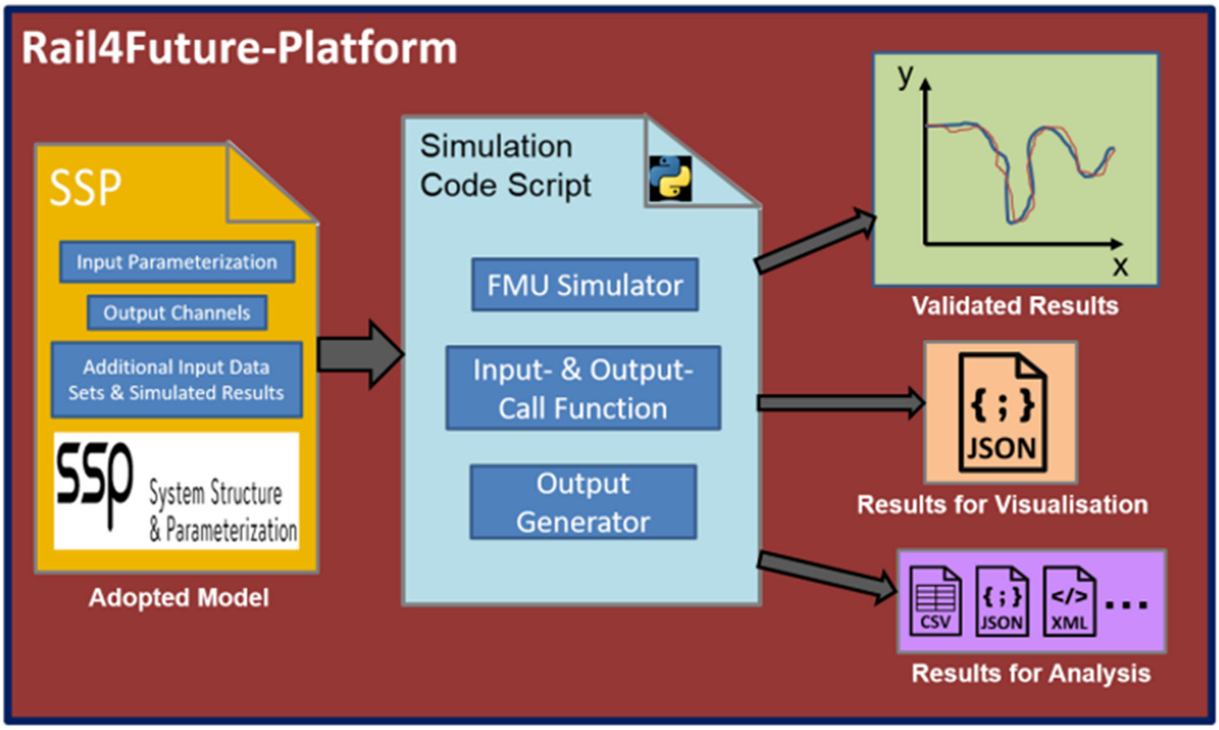

Fig. 1b) Model Simulation Approach. [1]

Fig. 2a and 2b show two use case examples of the simulation approach: residual life time (RLT) calculation of a steel bridge & multibody simulation (MBS) of a two-bogie railway vehicle (see Kugu et.al. [1] for further information about the integration of the two use cases into the R4F Platform).

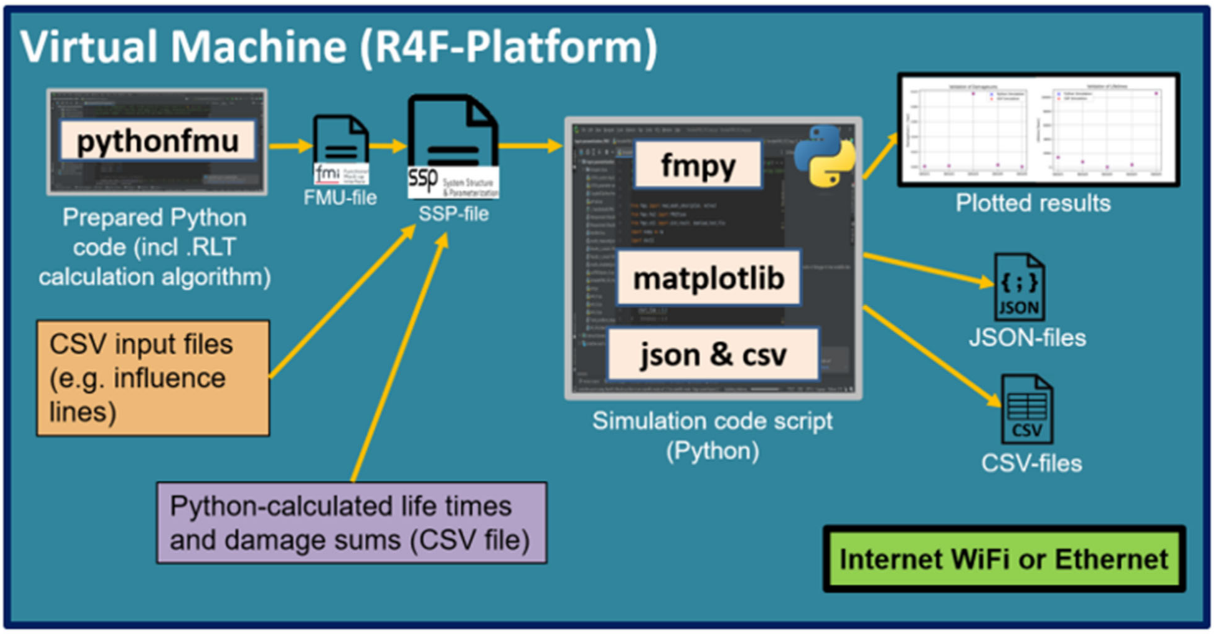

Fig. 2a) Simulation of the RLT bridge. [1]

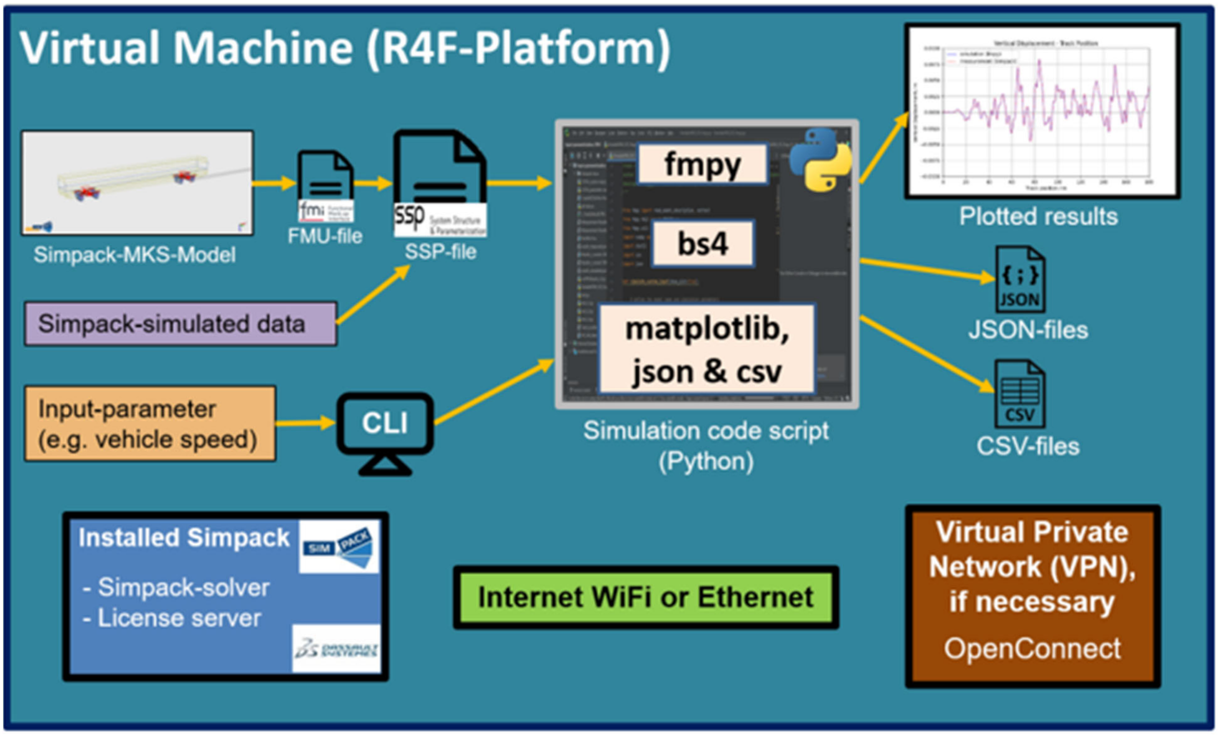

Fig. 2b) Simulation of the MBS vehicle. [1]

6.3 Model reduction and simplification

In order to reduce the computational complexity of the used models we consider hereby two main approaches. First classical approaches involving advanced modeling techniques and model reduction methods and second new AI methods. These are discussed in this section.

Model reduction is a critical process in computational modeling, especially when dealing with complex systems, primarily aimed at managing and mitigating the computational complexity inherent in detailed, high-fidelity models. High-complexity models, while accurate and detailed, often require significant computational resources and time to simulate, making them impractical for applications such as real-time simulations, optimization, or control tasks. Simplified models run faster and require fewer computational resources, which is crucial in scenarios where multiple simulations are needed, such as in optimization problems, parameter sweeps, or uncertainty quantification. In control systems, real-time decision-making is essential, and high-fidelity models may be too slow to provide timely responses, whereas reduced models can offer the necessary speed without sacrificing too much accuracy. Some applications, like embedded systems or mobile platforms, have limited computational power, making it feasible to deploy complex functionalities through reduced models.

6.3.1 Classical Approaches

One part of the strategy is to use simplistic models, which do not entail more detail as necessary which was demonstrated for example with the models used in the VTI use case. The only drawback to this is that it is often hard to automate. This is because finding a simpler model needs expert knowledge and often creative ideas to reduce the complexity in a way that does not lead to wrong results, except in the cases where model reduction approaches are well known and understood (e.g. in linear elastic cases where the dynamics can be reduced with help of the modal basis). Hence why AI and data driven approaches are used as well as they can be better formulated in terms of algorithmic procedures which in turn leads to easier automation of said procedures. AI Methods will be discussed in the following section.

6.3.2 AI Methodologies

A holistic railway infrastructure digital twin (DT) platform is sophisticated and consists of a series of submodels (e.g., turnouts, tracks, vehicles, etc.) that are built through various methodologies and software. However, integrating these submodels into the DT platform is tremendously challenging due to considerable computational complexity, software and interface restrictions. To this end, we propose to utilize a surrogate modeling approach to offer an effective solution by reducing the computation time and unifying the integration interfaces of different submodels. In this report, we designed a machine learning (ML) based surrogate modeling methodology for the submodel integration in the holistic railway infrastructure DT platform and illustrated the methodology through a case study. In this case study, an ML-based surrogate model for multibody simulation of railway vehicle-track dynamics is created, which can replace the railway vehicle-track simulation executed with the Multibody Dynamics (MBD) Simulation commercial software SIMPACK. The well-built ML model can accurately and quickly predict the vehicle-track system's dynamic responses to different track irregularities. Besides, we have validated the reliability of this methodology with input data of different dimensions and applied different algorithms used in developing the surrogate model. In the end, the integration process of the ML-based surrogate model into the DT platform through a standardized open-source Functional Mock-up Interface (FMI) is also proposed.

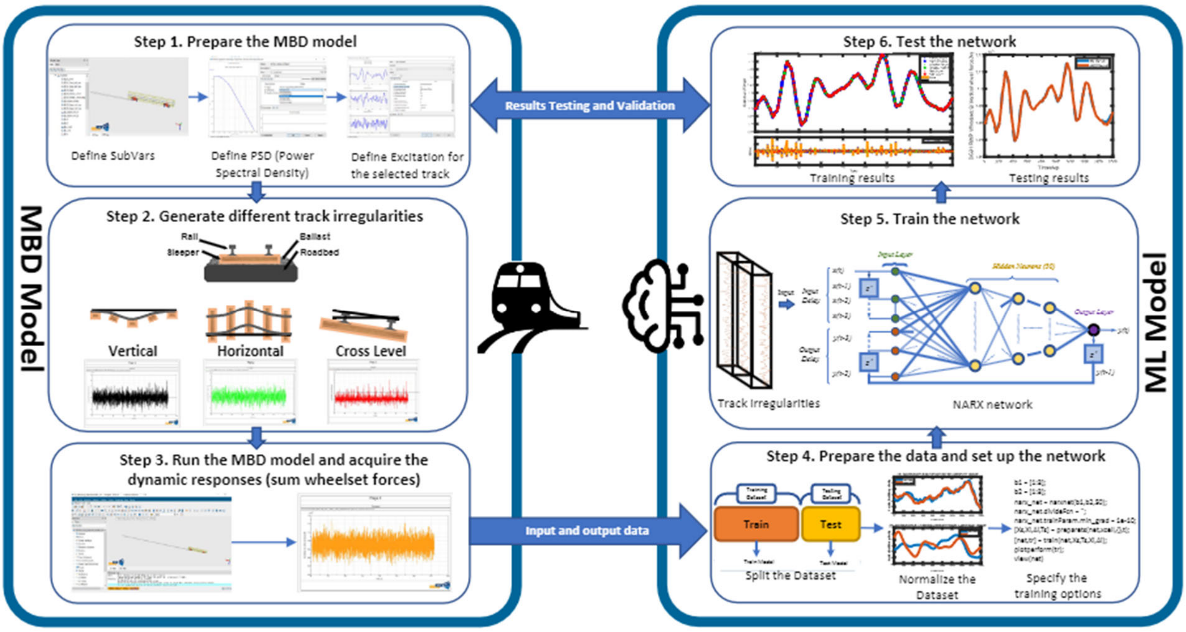

Fig. 3) Landscape of the ML-based surrogate modeling methodology [4]

The developed surrogate modeling methodology shows great promise owing to its high fidelity, which is verified by the measurement data collected from the Austrian national railway track system. Furthermore, this approach can also be applied to other submodels and help to build the holistic railway DT platform collaboratively.

6.4 Visualization

A digital twin, particularly of something as varied and large as a railway infrastructure network, is a highly complex tool. Visualization plays a big part in making this tool accessible and useful to end users.

There are multiple challenges when it comes to visualization of digital twins, especially large scale digital twins. Railway networks consist of vast amounts of data from multiple sources, and in a variety of formats and modalities. User groups are varied, with different requirements for technical experts and management or public relations. Different parts of the railway network (tunnels, bridges, tracks, etc.) have different visualization requirements.

To reduce complexity for users we propose using different user groups to hide complexity where possible but provide flexibility and details where necessary. Providing options for visualizations and simulation steering is necessary to allow for different use cases and a greater flexibility of the platform. However, too many options that are not necessarily relevant for answering a user's question about the data can lead to confusion, slower task completion, or mistakes. To avoid this, we hide options and features that are not relevant or necessary to certain user groups, while providing choice and granularity to others. In our prototype, we implement two user groups to illustrate this. Expert users get access to options like lookup granularity or additional simulation steering options. For normal users we focus on reducing complexity to a minimum.

Another way we reduce complexity via visualization is by encoding infrastructure health parameters in visual variables. Assume the goal of a user is to get an overall impression of infrastructure health of a railway network. We encode infrastructure elements and values like their remaining lifetime (or similar parameters) as icons on a map. The icon reflects the type of infrastructure element (bridge, tunnel, etc.), the colour the overall condition of that element.

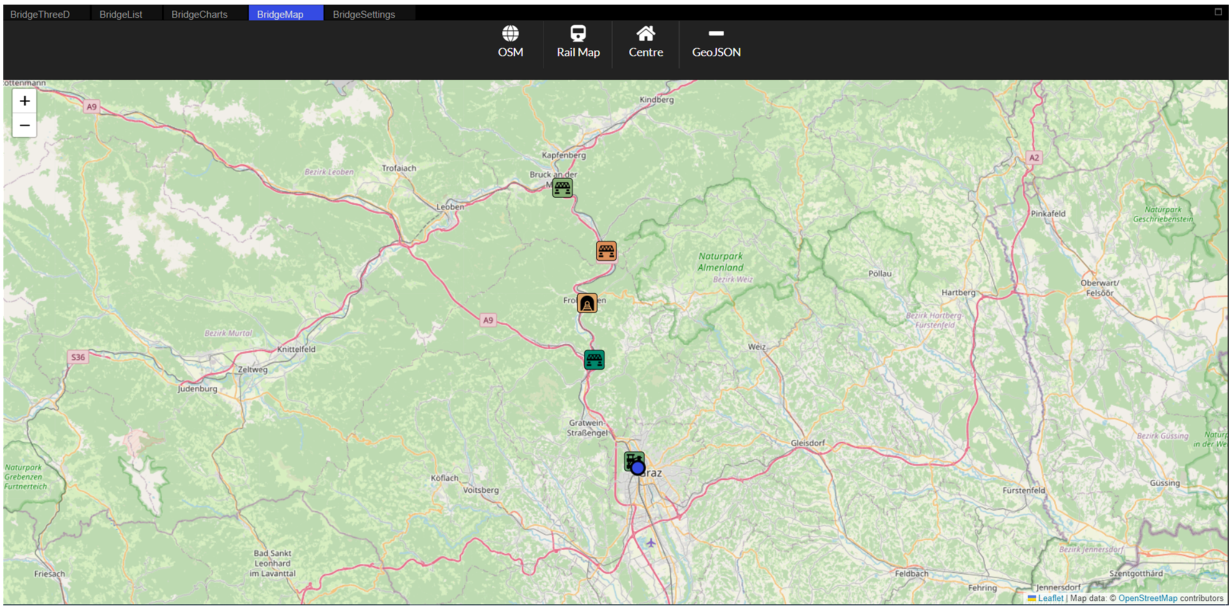

Fig 4) Visualization of infrastructure elements health status

In general, one use case requires multiple different sets of data, possibly from different sources. To hide this complexity from the end-user, we devised a metadata format for use cases. Each use case has a metadata file, in which we specify which data is necessary, an URL to that data, and other metadata such as labels and descriptions. With the content of this file we can adapt and enrich the graphical user interface of a use case. This conceals data specifics from end users while offering a flexible system for data management and integration.

7 Conclusion

The report highlights several crucial aspects of managing and optimizing railway simulation models within the R4F Platform. Effective orchestration, deployment, and execution of simulations are essential for handling the complexities of simulation tasks. The use of graph-based approaches and co-simulation process graphs facilitates seamless deployment and management of simulations, addressing challenges related to data exchange and the use of specialized software.

Standardizing simulation units is critical for achieving tool-independence and portability. The adoption of standards like the Functional Mockup Interface (FMI) and System Structure and Parameterization (SSP) enables efficient model adaptation, encapsulation of intellectual property, and seamless exchange of parameters between different models. This approach ensures that various railway assets can be integrated into the R4F Platform in a consistent and secure manner.

Model reduction and simplification methodologies play a vital role in managing computational complexity. Classical approaches focus on using simplistic models that contain only necessary details, although these methods lack automation. AI methodologies, such as machine learning-based surrogate modeling, provide a promising alternative by reducing computation time and unifying integration interfaces. These AI methods have been validated through case studies and show high fidelity in predicting dynamic responses, facilitating their integration into the digital twin platform.

Visualization is a key component in making digital twin tools accessible and useful to various user groups. Addressing the challenges of visualizing complex and large-scale railway networks involves tailoring the interface to different user needs. Simplifying the interface for normal users while providing detailed options for expert users helps manage complexity. Encoding infrastructure health parameters in visual variables, such as icons on a map, provides intuitive and immediate insights into the overall condition of infrastructure elements. The use of metadata formats for user cases further streamlines data management and integration, concealing data specifics from end users and enhancing the flexibility of the platform.

Overall, the combination of standardized interfaces, advanced model reduction techniques, and user-friendly visualization strategies ensures that the R4F Platform can efficiently manage and optimize railway simulations, making it a powerful tool for both technical experts and broader user groups.

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8 References

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