Rail4Future

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D1.3.2 Generic Model definition for multi-level optimization (M14)

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1 Executive Summary

This report presents a generic model definition for multi-level optimization in railway systems, which encompasses different model types and their corresponding use cases relevant to railways. The methodology for developing and implementing this model is outlined, alongside a modular and scalable architecture - Rail4Future (R4F) platform that integrates various components and subsystems of the railway system, such as the track, trains, and other systems. Mathematical, MBD, and ML models are developed to represent the railway system at different levels of abstraction and granularity. The report not only offers insights into the integration process of multi-level models into the R4F platform but also highlights the proposed model definition and integration methodology as beneficial for enhancing system effectiveness. Additionally, it concludes by recommending further research and development to refine the model and its implementation methodology with the aim of improving railway system performance. As a valuable resource, this report provides insights for researchers and practitioners seeking to optimize railway systems through multi-level modeling and digital twin technology.

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3 Description

A railway system consists of multiple levels, including the track level, train level, etc. Each of these levels interacts with the others to form a complex system that requires optimization at multiple levels. For example, optimizing train dynamics requires consideration of the track infrastructure, train systems, and some other factors. Therefore, a simulation model platform for the railway digital twin system should consider multiple levels and their interactions.

The generic model definition of a railway digital twin system for multi-level optimization can be structured as follows:

3.1 System Architecture:

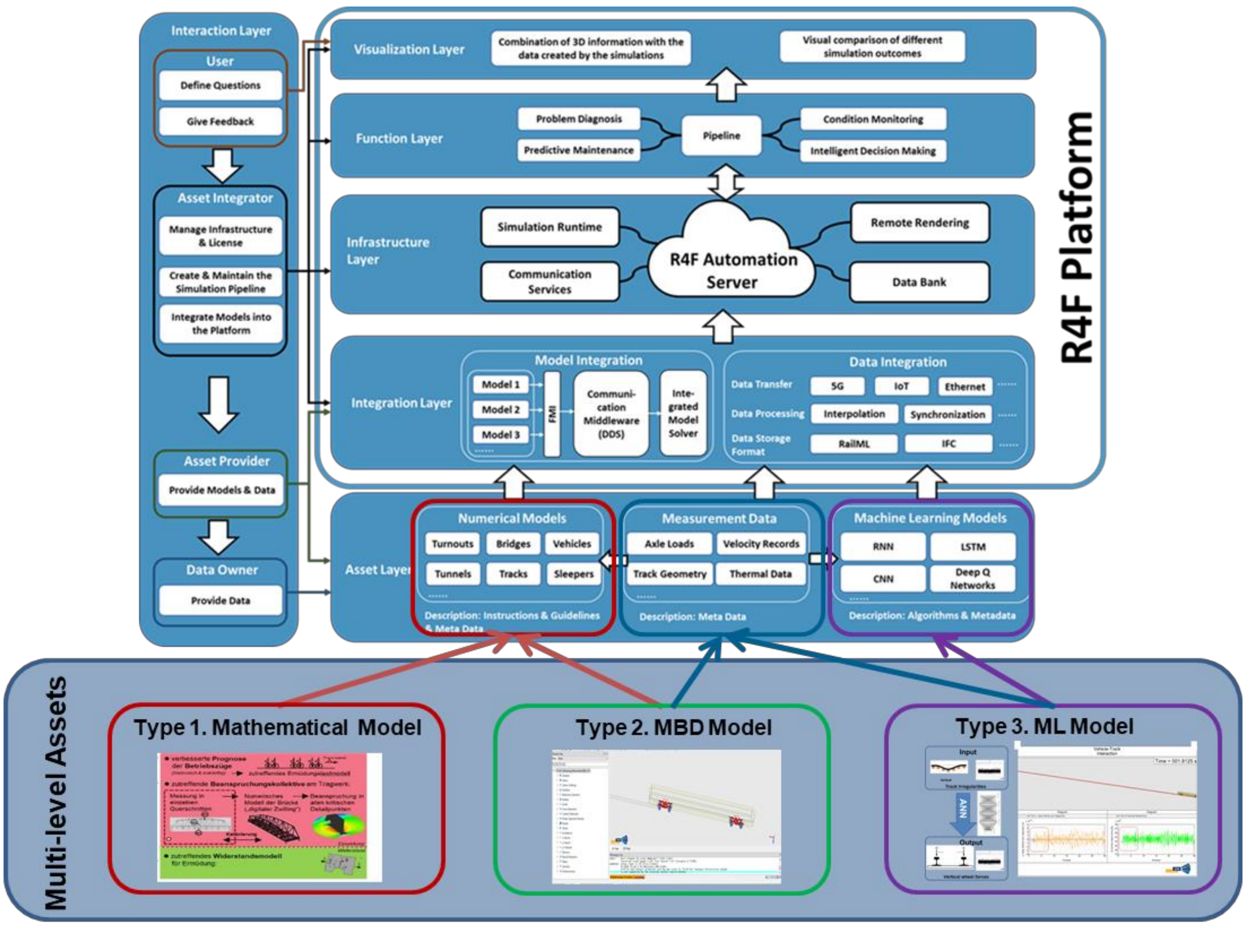

Fig. 1. The R4F Platform with Multi Level Assets

The railway digital twin system should have a modular and scalable architecture that can integrate different components and subsystems of the railway system, such as the track, trains, and other systems. The architecture should allow for real-time data exchange and synchronization between the virtual and physical systems. Based on these requirements, we have developed a conceptual model-based digital twin platform to integrate different assets. The R4F platform may ensure that reliable and valuable data can continuously flow throughout the whole life span of the holistic system and its subsystems, which may help build a fully connected and digitized railway infrastructure system. We first identify the crucial requirements of the R4F platform to define its essential characteristics, which ensures that the platform works consistently and reliably. After that, a 6-Layer based architecture of the proposed R4F platform with multi-level assets is presented as the generic system architecture.

3.2 Model Development:

The railway digital twin system should develop different types of models to represent the railway system at different levels of abstraction and granularity. The models should capture the railway system's physical, operational, and maintenance aspects and be validated against real-world data. In this section, different types of models are presented with a real usecase for each model type.

3.2.1 Type 1 - Mathematical Model: RLD Model (Restlebensdauer Model)

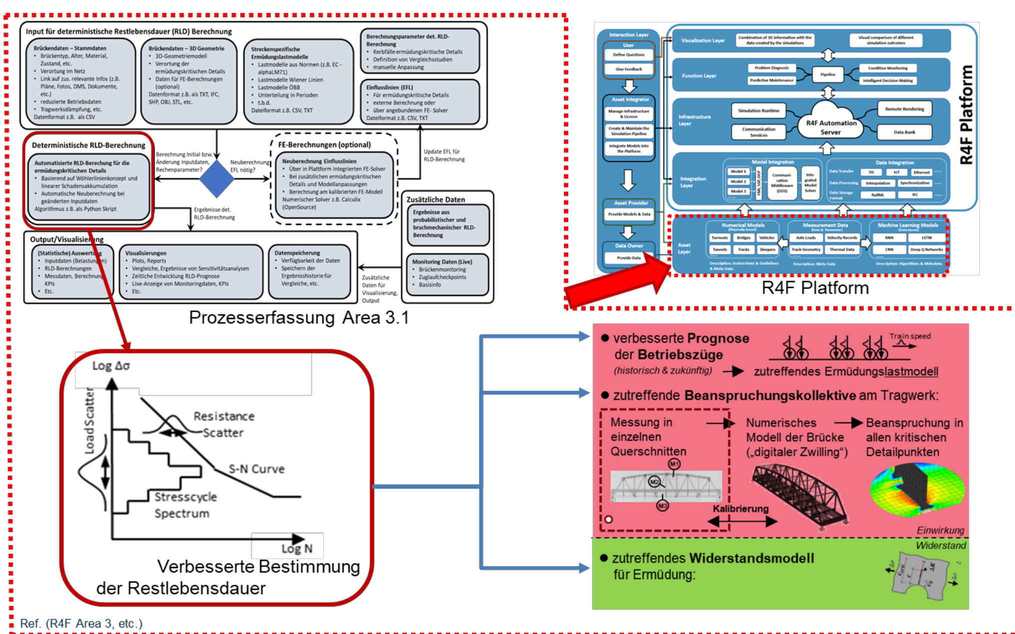

Fig. 2. RLD Model

This subsection presents a comprehensive overview of the model utilized to calculate the residual lifetime of a steel bridge. The process involves several domains, including input, influence lines, detail categories (notch cases), a deterministic RLD calculation algorithm in the form of a Python script provided by the AIT, and output/visualization for statistical evaluation, reporting, plotting, and data storage purposes. The framework's effectiveness in determining the remaining service life of the steel bridge is illustrated in Figure 2, which depicts the typical approach for conducting the calculation. Additionally, a finite element (FE) calculation of the bridge can be conducted for visual analysis if necessary. The simulation process is enabled by different CSV files that register all inputs provided by the end user and generate outputs for use by the Python code in conducting the calculation. By ensuring accuracy and reliability, the model enables well-informed maintenance and repair decisions, contributing to the longevity and safety of the steel bridge.

3.2.2 Type 2 - MBD Model: Manchester Erlkönig Model

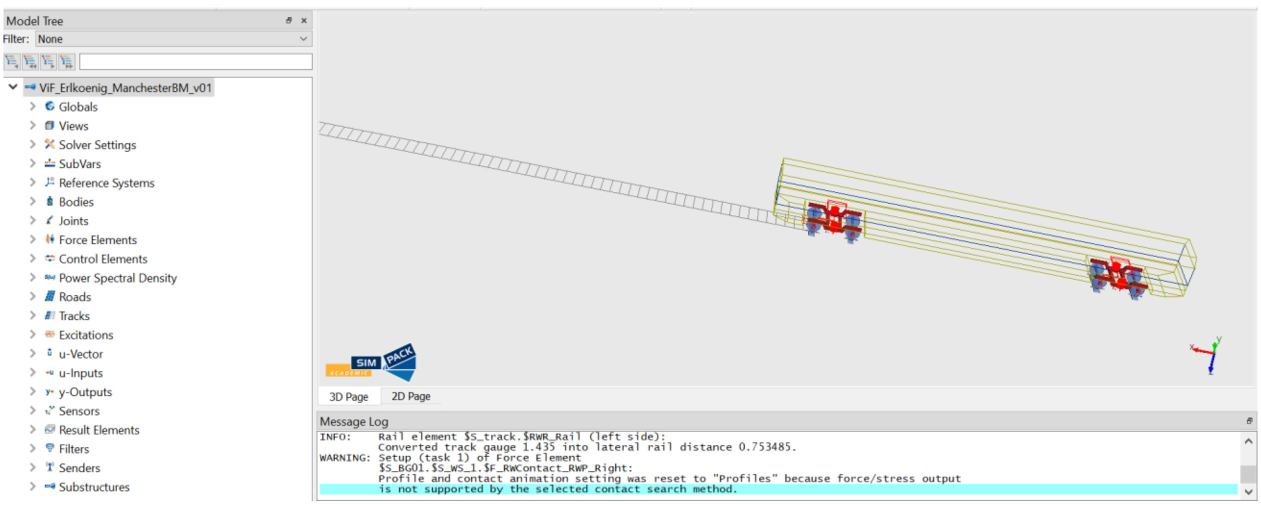

Fig. 3. MBD model

This subsection provides a detailed explanation of the MBD model, i.e., the Manchester Erlkönig Model. The MBD model is an essential tool for simulations of various scenarios based on inputs such as scenario- and model parameters, including variables such as vehicle speeds, additional passenger and luggage masses, track arc radius, and superelevations. By modeling these different scenarios, the MBD model can offer valuable insights into the dynamic behavior of railway vehicles in different situations. One crucial aspect of this dynamic behavior is the wheel and track interaction. The dynamic forces generated by this interaction can be substantial, particularly in the presence of irregularities in the track geometry. Large dynamic forces can damage vehicle wheels, leading to derailments in the worst cases. Therefore, it is essential to have a comprehensive understanding of vehicle-track dynamics to ensure railway safety. To achieve this, the MBD model is constructed using the commercial software

SimPACK, which offers a reliable and robust way to analyze the dynamic forces acting on the track elements and the vehicles. Researchers and engineers can use this software to develop the MBD model and gain valuable insights into the forces during railway operations. These insights can inform the design and operation of railway systems, leading to safer and more efficient transportation.

3.2.3 Type 3 - ML Model: ML based Surrogate Model for MBD Simulation

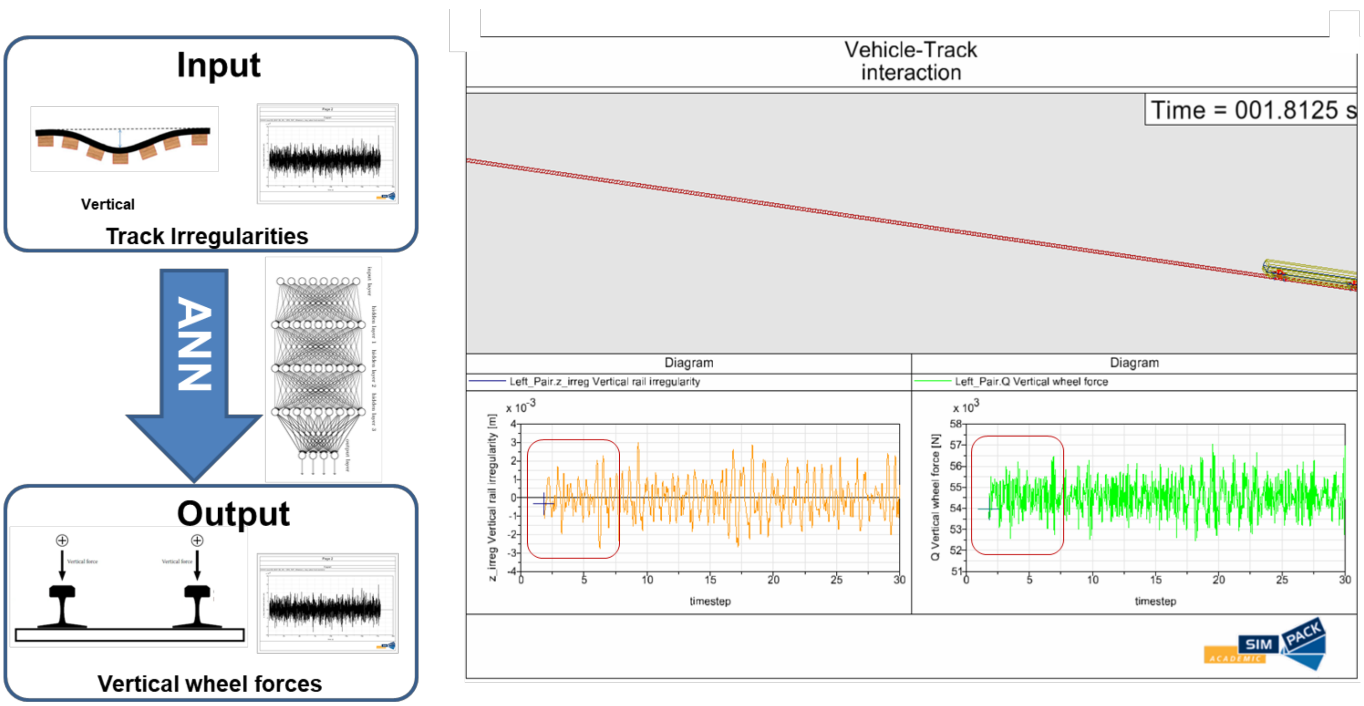

Fig. 4. ML-based Surrogate Model

In this subsection, we utilize a surrogate modeling approach to offer an effective solution by reducing the computation time and unifying the integration interfaces of different submodels. In Project 1.3, we designed a machine learning (ML) based surrogate modeling methodology for the submodel integration in the holistic railway infrastructure DT platform. We also 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. The developed surrogate modeling methodology shows great promise owing to its high fidelity, which is verified by the measurement data collected from natural railway track systems. Furthermore, this approach can also be applied to other submodels and help to build the holistic railway DT platform collaboratively.

3.3 Integration Methods

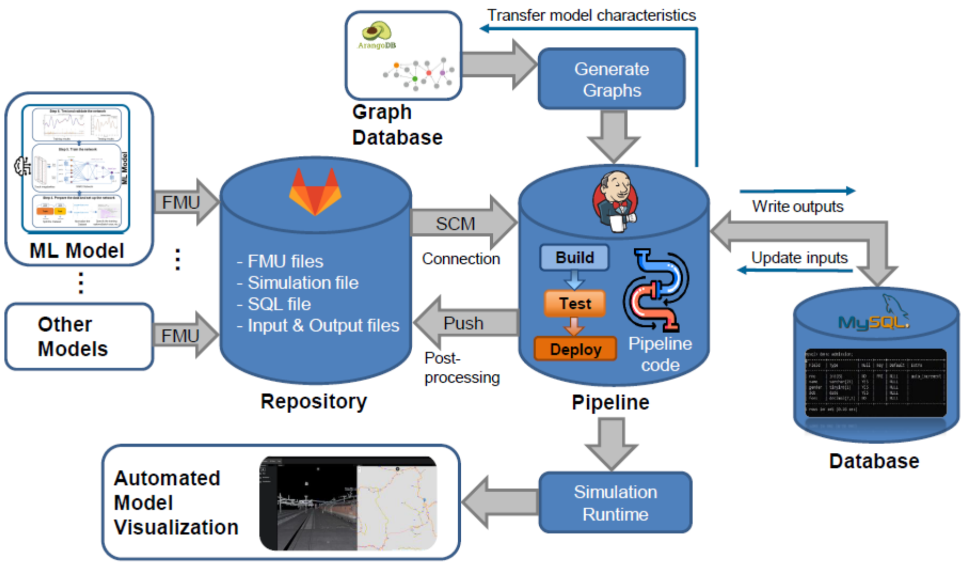

Fig. 5. Flow chart of model integration

This subsection introduces the integration process of the multi-level models into the R4F platform. Integrating multi-level models into a DT platform can offer significant benefits in terms of improving the effectiveness of the DT. Multi-level models involve modeling a system at different levels of detail and complexity, from the component to the system level. These models can capture various factors that influence the system's behavior, including physical processes, control systems, and environmental conditions. However, integrating these models into a DT platform can be challenging due to the diverse data types and formats. An integration process is necessary to ensure that the different models can communicate with each other and exchange data effectively. This process typically involves defining a common language or data model that all the models in the system can use. The integration process also allows for seamless data exchange between different model levels. For example, data generated at the component level can be used to update the system-level model, which can then be used to inform decision-making and optimize the system's performance. This approach can enable engineers to detect and diagnose problems in the system more quickly and accurately, leading to more efficient and effective maintenance and repair.

As presented in Fig.5., the model will first be translated into the FMU format (Functional Mock-up Unit, the simulation unit of the FMI) to make it tool-independent and, therefore, interoperable with other models. Then, the FMU files will be uploaded into a repository (e.g., GitLab repository), which provides a storage location for their related codes and other files. In the repository, the users can design, control and optimize the integration process of the model and enhance its interoperation with other models. Afterward, the model will undergo a simulation pipeline methodology, such as Jenkins Pipeline, which helps to continuously and automatically organize the calculation and interaction of the multi-level optimization. The pipeline is connected to the repository through the Source Code Management (SCM) system, which can be used to track and control changes in the repository. In our case, the pipeline executes the integrated model by running a simulation file (e.g., Python file) in a pipeline code that controls the functionality of the pipeline by defining necessary credentials for automatically authorized logins and different stages for step-by-step simulation workflow. Besides, input and output files in the repository get updated simultaneously (e.g., through the “push” command) for the users to check the simulation inputs and results, and then the pipeline gets updated inputs to execute another simulation. As a result, the pipeline can automatically integrate and deliver the model in the platform continuously. Additionally, a database management system (DBMS), e.g., MySQL, will be implemented to store, exchange, and archive the input and output data. Moreover, the inputs and outputs in the database can also be automatically redirected to the visualization interface for the end user through the execution of a query code file by the pipeline after the simulation runtime. Besides, the semantic approach is planned to be involved in the pipeline so that all characteristics of the integrated model (inputs, outputs, simulation workflow, data and submodel dependencies) can be interconnected and presented through a graph database system, such as ArangoDB. In the end, the visual output of the simulation runtime is expected to be presented for the end user to monitor the whole vehicle-track dynamics and to control it by input parameters through a web-based user interface system.

3.4 Conclusion

In conclusion, the development of a railway digital twin system for multi-level optimization is crucial for improving the accuracy and effectiveness of the railway system. The railway digital twin system should have a modular and scalable architecture (the R4F platform), allowing for quick data exchange and synchronization between the virtual and physical systems. In this report, we have listed three different types of models, which are demonstrated with respective usecases., i.e., Type 1 Mathematical Model (RLD Model), Type 2 MBD Model (Manchester Erlkönig Model), and a Type 3 ML Model (ML-based Surrogate Model for MBD Simulation). These models are integrated into the railway digital twin system via Functional Mock-up Units as a "generic model definition." In the end, the generic model definition for multi-level optimization may ensure that reliable and valuable data can continuously flow throughout the whole life span of the holistic system and its subsystems, helping to build a fully connected and digitized railway infrastructure system.