Optimal network electrification plan for operation of battery-electric multiple unit regional trains

M. Kapetanović[a,*], N. Bešinović[a], A. Núñez [b], N. van Oort[a], R.M.P. Goverde[a]

[a] Department of Transport and Planning, Delft University of Technology, Delft, The Netherlands
M.Kapetanovic@tudelft.nl, N.Besinovic@tudelft.nl, N.vanOort@tudelft.nl, R.M.P.Goverde@tudelft.nl
[b] Section of Railway Engineering, Delft University of Technology, Delft, The Netherlands
A.A.NunezVicencio@tudelft.nl
* Corresponding author

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1 INTRODUCTION

The Netherlands have one of the highest rail electrification rates in the EU with over 75% of the railway network electrified (European Comission, 2018), offering environment-friendly trains operation. However, in order to achieve carbon neutral railway sector by 2050, significant investments are required to further improve environmental performance from trains operation, especially in regional non-electrified networks with passenger services typically provided by diesel multiple unit (DMU) vehicles. Due to their low utilization, full electrification of such networks is often not economically viable, thus solutions are mainly sought in alternative propulsion system technologies, such as hydrogen fuel-cell multiple unit (FCMU) and battery-electric multiple unit (BEMU) vehicles (Klebsch et al., 2019). One of the main challenges in introducing BEMU trains is determining the electrification plan for the railway network, while satisfying requirements related to quality of service, maintaining current timetable, and vehicle-specific constraints. Previous research on BEMUs operation is mainly focused on continuous partial lines electrification, or eventually limited scenario analysis on intermittent electrification (Abdurahman et al., 2021), with the optimization-based methods still lacking in the literature. This study aims to fill this gap by proposing a method for developing an optimal electrification plan, while minimizing total costs and considering several electrification alternatives for each track section.

2 METHODOLOGY

The proposed methodology is based on a simulation-based optimization of railway network electrification plan, with the objective to minimize the overall monetary costs. Three alternative electrification options are considered for each track section: (i) complete section electrification (between two consecutive stops) (Network Rail, 2015), (ii) acceleration catenary (Mwambeleko et al., 2020), and (iii) rapid ESS charging facilities during stops (Ahmad et al., 2021). The overall costs include the partial track electrification costs proportional to the length of overhead catenary installed, and the costs for a traction electricity provision infrastructure, proportional to a number of separated electrified sections, i.e., number of power substations.

2.1 Modeling of battery-electric multiple unit

The propulsion system architecture for the BEMU vehicle is shown in Figure 1. On electrified track sections electricity is supplied from the catenary via pantograph, connected to the DC link via a power converter. BEMU is propelled entirely by AC electric traction motors located at the drive shaft, and connected to the DC link via bi-directional DC/AC converters. Additional on-board consumers include auxiliary systems such as lighting, compressors and HVAC components. Lithium-ion battery-based energy storage system (ESS) is being charged from the traction grid, where available, and from the regenerative braking energy. In non-electrified track sections, entire power demand for traction and auxiliary systems is provided from the ESS. To achieve realistic estimations on BEMU's powertrain dynamics, a detailed simulation model based on a backward looking quasi-static simulation approach (Pröhl, 2017) is adopted. The dynamics of each component is modeled in MATLAB®/Simulink© using the OPEUS Simulink library - a result of the built up knowledge from several European projects (Shift2Rail, 2021), and validated in a number of studies, including authors' previous work (Kapetanović et al., 2021a; Kapetanović et al., 2021b). The simulation model requires technical specifications for variety of system components and infrastructure related characteristics as inputs, while the main output is given with the ESS state-of-charge (SOC). For a particular solution to be feasible, ESS SOC must remain within the permissible limits defined by a manufacturer.

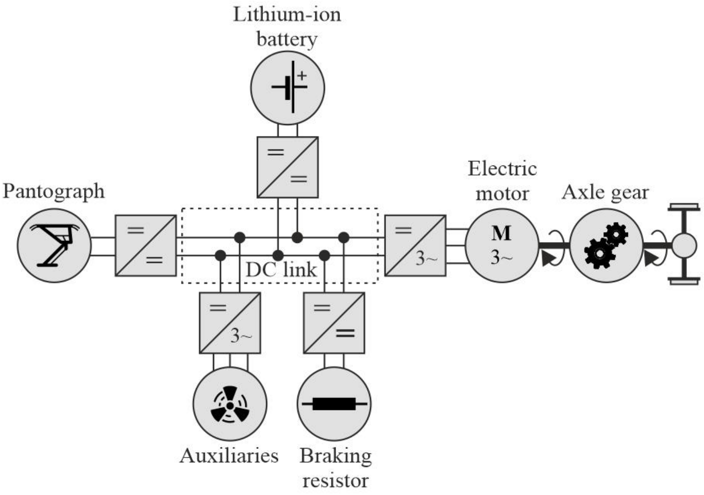

Figure 1 – *Schematic representation of a propulsion system for battery-electric multiple unit vehicle*

2.2 Optimization framework for the network electrification plan

The optimization algorithm is presented in Figure 2. Since transport services can stretch over multiple branches, the first step is to map all railway services to a physical railway network. For each railway service, a matrix containing all possible electrification configurations is constructed, based on the introduced three alternative electrification options for each track segment covered by the service. Using nested search architecture (Silvas et al., 2016), each electrification configuration for each service is evaluated using the previously described simulation model, and the corresponding costs are calculated. For unfeasible solutions where ESS SOC drops below the lower limit (e.g. 10%), costs are assigned an infinite value. Once all possible solutions are evaluated, the cost-optimal electrification plan for the whole network is derived by solving the mixed integer programming (MIP) problem using binary decision variables linked to each of the three electrification options, while satisfying condition that only one electrification option can be assigned to each track segment.

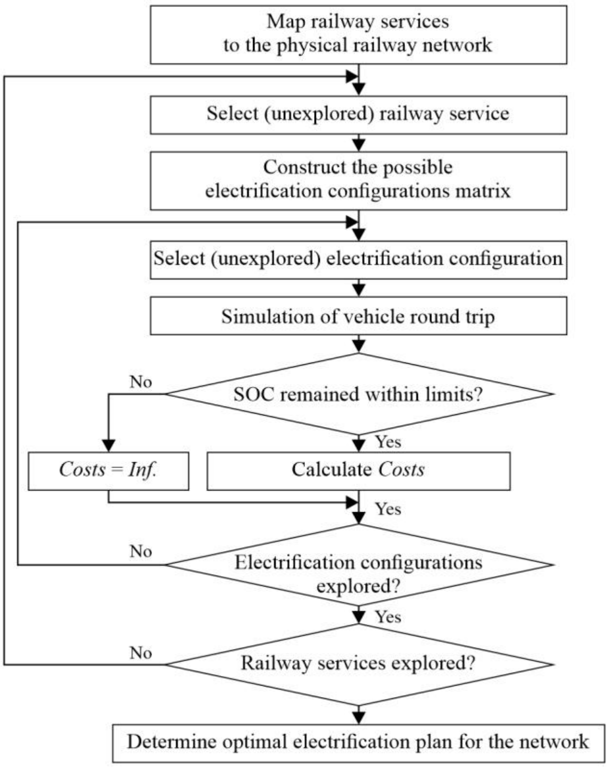

Figure 2 – *Flowchart for the proposed railway network optimization algorithm*

3 DUTCH CASE STUDY

3.1 Regional railway network in the northern Netherlands

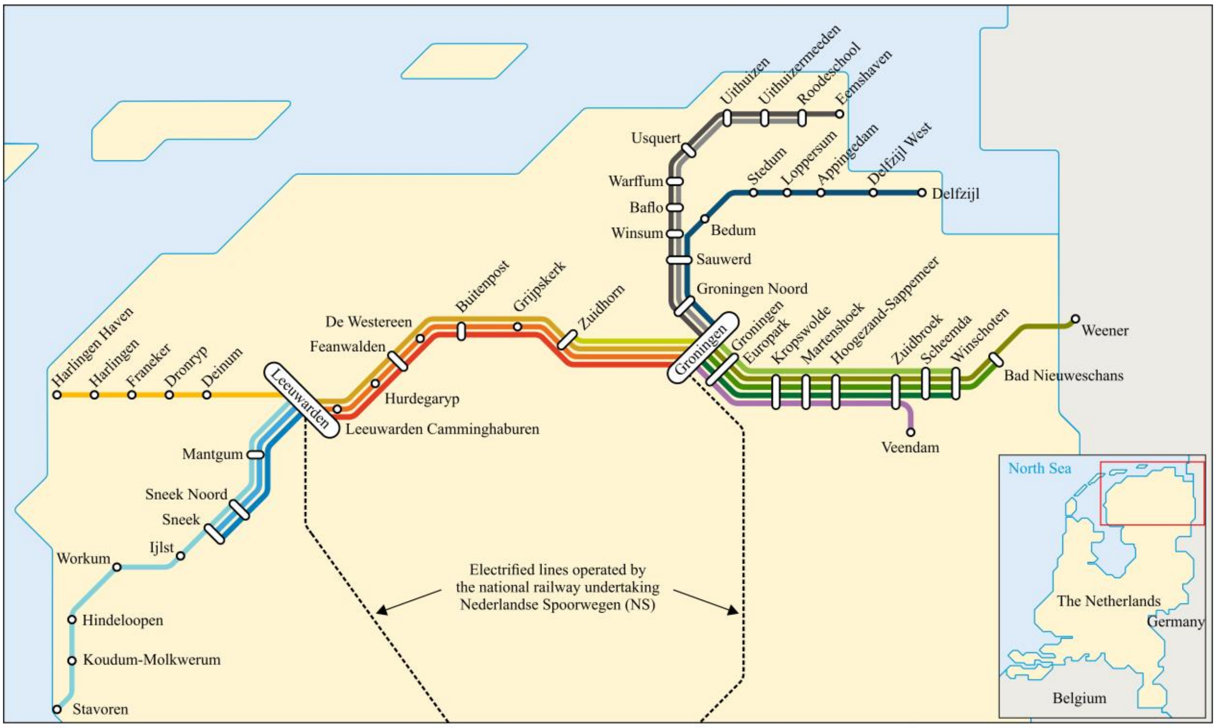

Figure 3 – *Schematic representation of regional railway network in the northern Netherlands, with indicated different passenger transport services*

Presented methodology will be applied in a case study of regional non-electrified railway network in the northern Netherlands. The network encompass seven railway lines in provinces Friesland and Groningen, with provided sixteen different transport services shown in Figure 3. Detailed infrastructure characteristics including track geometry, speed limits and timetable are provided by the railway undertaking Arriva.

3.2 Reference battery-electric multiple unit

A bi-mode hybrid two-coach DEMU, based on a new platform WINK (abb. for *Wandelbarer Innovativer Nahverkehrs-Kurzzug*, in English, *convertible innovative commuter short train*) will be used as a reference vehicle in this study. Introduced in the network in 2021, these hybrid DEMUs are aimed to be converted to their BEMUs counterparts by replacing the diesel generator and fuel tank with additional battery power-packs (Stadler, 2020). Detailed vehicle characteristics and parameters used in the analysis are provided by the vehicle manufacturer Stadler.

References

Abdurahman, B. M., Harrison, T., Ward, C. P., & Midgley, W. J. B. (2021). An investigation into intermittent electrification strategies and an analysis of resulting CO2 emissions using a high-fidelity train model. *Railway Engineering Science*, *29*(3), 314–326.

Ahmad, S., Spiryagin, M., Cole, C., Wu, Q., Wolfs, P., & Bosomworth, C. (2021). Analysis of positioning of wayside charging stations for hybrid locomotive consists in heavy haul train operations. *Railway Engineering Science*, *29*(3), 285–298.

European Comission. (2018). *Electrified railway lines*. https://ec.europa.eu/transport/facts-fundings/scoreboard/compare/energy-union-innovation/share-electrified-railway_en

Kapetanović, M., Núñez, A., van Oort, N., & Goverde, R. M. P. (2021). Reducing fuel consumption and related emissions through optimal sizing of energy storage systems for diesel-electric trains. *Applied Energy*, *294*, 117018.

Kapetanović, M., Vajihi, M., & Goverde, R. M. P. (2021). Analysis of Hybrid and Plug-In Hybrid Alternative Propulsion Systems for Regional Diesel-Electric Multiple Unit Trains. *Energies*, *14*(18), 5920.

Klebsch, W., Heininger, P., & Martin, J. (2019). *Alternatives to diesel multiple units in regional passenger rail transport: Assessment of systemic potential*. VDE Report.

Mwambeleko, J. J., Hayasaka, T., & Kulworawanichpong, T. (2020). Enhancing conventional battery and contact line hybrid tram system with accelerating contact lines. *IET Electrical Systems in Transportation*, *10*(1), 105–115.

Network Rail. (2015). *A Guide to Overhead Electrification*. https://www.bathnes.gov.uk/sites/default/files/sitedocuments/Planning-and-Building-Control/Planning/nr_a_guide_to_overhead_electrification.pdf

Pröhl, L. (2017). *OPEUS Deliverable DO2.1 - OPEUS simulation methodology, EU-project OPEUS (S2R-OC-CCA-02-2015).*

Shift2Rail. (2021). *OPEUS - Modelling and strategies for the assessment and OPtimisation of Energy USage aspects of rail innovation*. https://projects.shift2rail.org/s2r_ipcc_n.aspx?p=OPEUS

Silvas, E., Hofman, T., Murgovski, N., Etman, P., & Steinbuch, M. (2016). Review of Optimization Strategies for System-Level Design in Hybrid Electric Vehicles. *IEEE Transactions on Vehicular Technology*, *66*(1), 1–1.

Stadler. (2020). *WINK BMU / WINK ZERO EMISSION: Arriva Netherlands, Noordelijke Lijnen franchise - Preliminary datasheet*. https://www.stadlerrail.com/media/pdf/warr0420e.pdf

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