X2Rail-4

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1 Executive Summary

The aim of the studies on migration for OTI is to show under which conditions the new technology should be introduced to be implemented as optimally as possible for the overall railway system and the stakeholders acting in this ecosystem. The analysis was carried out in parallel with the development of the three OTI product classes developed within X2Rail-2 and X2Rail-4 and considers examples of their possible applications in the various market segments. For freight transport in particular, attention was drawn to taking appropriate account of the complexity arising from the distinction between block trains and single wagonload traffic. The deliverable thus addresses the task described in the contractual documents. It should be noted that the application had to be for generic example scenarios.

In the context of this project, the focus was purely on the OTI. The consideration of additional boundary conditions (arising e.g. from ETCS, DAC, ...) has to be done in the context of the real roll-out under the then prevailing conditions. The developed methodology provides a good starting point for this.

The optimization criterion for the migration was defined as the saving potential resulting from the removal of axle counters and track circuits that are no longer required. The optimization potential lies in the fact that, if trains are equipped with OTI in an optimised manner, track sections can dispense with axle counters and track circuits as early as possible without restricting the operating program. By saving these field elements, their operating costs and potential reinvestments are eliminated, so that an optimum can be achieved overall for the entire system. As part of an economic analysis, the effects were differentiated for infrastructure manager and wagon owner. The analysis has been done for two different migration paths as well as for a reference scenario (baseline).

Methodologically, an optimization model was newly developed for this project, which deals with the optimization criterion and the defined constraints and performs a mathematical optimization of the possible migration paths. This model was applied prototypically for the first time to a generic network with an operating program. The results show the potential of an optimization under the given input variables.

For subsequent projects, the developed computational model provides a tool that can be used to determine optimised migration strategies given the appropriate data input.

Likewise, there is potential for scientific follow-up to further develop and optimize the tool on the one hand and to make comparisons between the optimised results and, for example, non-optimised (random) migration processes or manually performed

optimizations on the other hand. In this way, for example, migration plans drawn up with human expertise could be reviewed and compared to computational results.

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3 Abbreviations and acronyms

Abbreviation / Acronyms	Description
DAC	Digital Automatic Coupling
EDDP	European DAC Delivery Programme
ETCS	European Train Control System
FRMCS	Future Railway Mobile Communication System
GoA	Grade of Automation
GSM-R	Global System for Mobile Communications – Rail
IM	Infrastructure Manager
IoT	Internet of Things
OTI	On-board Train Integrity
RU	Railway Undertaking
SPD	System platform demonstrator
TD	Technical demonstrator
TRL	Technical Readiness Level
WP	Workpackage

4 Background

Against the background of climate change rail offers opportunities for decarbonising mobility by ensuring green transport solutions. Extensive system improvements are needed to enable the railroad to perform this task. To be competitive and able to offer transport services at market price level of road and waterway it is an important task to reduce system costs. It is then however also necessary to be able to cope with an increased demand. Increasing rail capacity is possible, e.g. by shortening train headways. This requires rail operation in moving block, i.e. the introduction of train control systems like ETCS Level 3 for which on-board train integrity is an enabler. Another important issue is the reduction or limitation of operational costs of the rail system to cope with the rising costs. The task is to ensure and increase the competitiveness of rail transport, especially at railway lines with a lot of infrastructure field elements and low traffic volumes. An important starting point for cost reduction analysed in this report is the reduction of infrastructure elements responsible for the detection of train integrity which can be replaced by on-board technology.

To advance the two important aspects increasing capacity and saving costs, the use of on-board train integrity (OTI) can make a substantial contribution, as shown in the OTI Cost-Benefit-Analysis in X2Rail-2 and X2Rail-4 WP6 [1] [2]. The idea is to shift the train integrity check from the infrastructure to the vehicle. This enables the wide use of innovative train control systems and leads to cost savings due to fewer necessary infrastructure elements and reduction of field elements. So, on the one hand OTI is an enabler for ETCS Level 3, because it requires a mandatory OTI solution, and thus increased track capacity. On the other hand, OTI can contribute to the overall objective saving costs by the possibility to reduce field elements like axle counters, track circuits and other infrastructure elements because train integrity is checked by the train itself and not (only) by the infrastructure. OTI can be considered as enabler for saving costs in areas with less rail traffic (reduce most of the infrastructure elements) as well as on dense rail corridors (reduce infrastructure elements to a minimum or basic level). To take full advantage of the aforementioned benefits, an OTI solution has to be available for all trains on the line. This means that advantages rise with an increase of trains that are equipped with OTI. This aspect leads to the research question of this report, i.e. possible OTI migration strategies and their economic advantages in rail traffic in Europe. Various approaches are conceivable when introducing OTI. The stakeholders for example could achieve capacity gains as early as possible through OTI by equipping e.g. freight wagons and passenger trains on dense corridors with OTI as quickly as possible (neglecting possible quick wins on the infrastructure side on low density lines with fewer trains). On the other side the stakeholder could save costs as early as possible by reducing field elements as early as possible (slower increasing capacity gains are accepted in this case). The focus in this project is on freight traffic as well as on the market segments high-speed rail and regional traffic. An important point in possible migration scenarios is the distinction between different market segments such as high-speed, regional and freight. Depending on the market segment, different OTI classes and application scenarios are likely. A main objective of this task is to develop migration strategies for OTI tailored to the different market segments.

5 Objective / Aim

The aim of the work was to look at the introduction of OTI from different perspectives. The three OTI product classes should be considered in their areas of application as well as the various railway market segments, with particular attention being paid to the freight transport sector, as this is particularly complex in terms of optimised wagon equipment due to single wagon traffic.

To accompany the development of the on-board train integrity solutions up to TRL7, an outlook on the technology migration of the OTI is given. The work aimed at is to identify optimised migration paths for the rollout of OTI technology. To achieve this, boundary conditions are analysed in terms of surrounding migration strategies in the control and signalling of railway transport as well as migration conditions for the different market segments. Based on the technology specifications from the X2Rail-2 and X2Rail-4 projects, representative scenarios have been defined to apply the migration strategy. An optimization methodology was developed and computationally modelled and then applied to a railway network with an operating program. Based on the results of the optimization model, an economic evaluation of the different OTI migration strategies was performed. Life cycle cost analysis has been done to compare monetary effects of the different migration paths as well as the effects for different stakeholder.

6 Migration strategies

In this chapter, possible OTI migration strategies are considered. We first take a general look at selected migration strategies that have already been applied in the rail sector (section 6.1). For this purpose, we briefly describe concretely applied migration strategies and their most important characteristics.

With the knowledge of the technological context in which the rollout of OTI will take place, the options for OTI migration discussed in the project are then described and the optimization criterion is substantiated, which determines the methodology developed in the following sections. This defines the underlying migration strategy for OTI (section 6.2).

6.1 Related technologies and their migration activities

An OTI migration will not take place in isolation, but is accompanied by boundary processes that occur at the same time. Thus, it is important to place an OTI migration in the overall railway context and to consider numerous boundary conditions. These include, for example, parallel migration processes such as the migration from the legacy train control systems to the European Train Control System (ETCS), the conversion of the previous screw coupler in freight wagons to the automatic centre buffer coupler (digital automatic coupler - DAC), and innovations in the design of freight wagons (telematics, electrification, lightweight construction etc.). A selection of the most recent areas under migration within the railway sector will be given in the following chapters. However, the OTI migration considered in this project will not cover the coordination with all those different aspects, but will focus on the OTI system in principal.

For the OTI migration itself further boundary conditions are to be examined, so that a successful migration can be accomplished. It has to be clarified, if the necessary technology is available on time. For example, to establish full OTI functionality new technology like FRMCS (future railway mobile communication system - new standard for railway communication) is necessary. It is required because GSM-R cannot adequately meet the performance requirements for communication [3]. Regarding infrastructure it has to be clarified, where axle counters can be saved completely and where a minimum must remain, e.g. for operation in fall-back mode. For the migration phase, it is necessary to check whether sufficient workshop capacity is available for the conversion work on the freight wagons [4]. Since not all of these questions can be answered at present, assumptions will be made as necessary.

OTI is an important enabler for increasing capacity and saving costs, but equally important and necessary for OTI migration to be successful are the implementation of ETCS Level 3 and the DAC. Although the focus in this project is on the OTI migration strategy itself, the introduction and migration of ETCS and DAC cannot be disregarded in the later rollout as there are many interfaces, mutual influences and dependencies between OTI, ETCS and DAC (Figure 1).

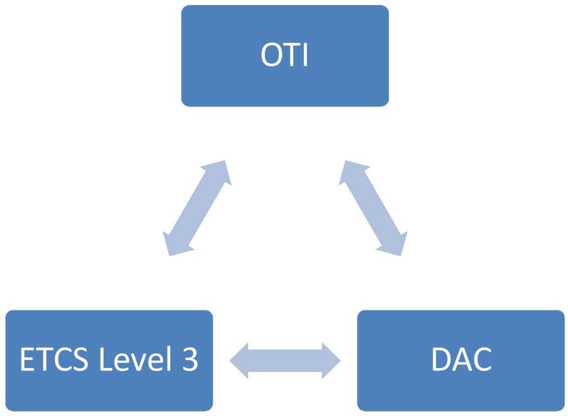

Figure 1: Mutual influences and dependencies between OTI, ETCS Level 3 and DAC

6.1.1 ETCS migration

Various migration approaches are conceivable for a nationwide introduction of ETCS. Numerous possible concepts have already been discussed among experts (e.g. in PhD thesis Lackhove “ETCS migration” [5]). Overall, two different approaches can currently be identified for the European ETCS migration. On the one hand, countries (e.g. Germany [6] [7]) choose the corridor approach, where the most important corridors are equipped with ETCS one after the other in order to supply important transport corridors (cf. Trans-European network TEN) with ETCS. The rest of the network will be retrofitted with ETCS much later. On the other hand, there are countries in Europe (e.g. Luxemburg [8]) that are completely converting their rail network to ETCS and equipping all lines with the technology, and doing so in a relatively short time and in the form of an overall program. Another important migration aspect is the definition of the time period during which dual equipment of vehicles and infrastructure is foreseen (this refers to the simultaneous presence of ETCS and Class B systems). The aim is to keep this period as short as possible.

The introduction of OTI provides the network operator with information about the train integrity of trains equipped with OTI technology. However, with this information it is not yet possible to operate at the absolute braking distance, if no corresponding train protection system is yet available. This means that the introduction of OTI can already achieve cost savings by eliminating or reducing the number of train detection system modules (e.g. axle counters) on the infrastructure without an increase in capacity by operating without fixed route blocks.

The ETCS without OTI functionality offers only marginal capacity increases compared with conventional continuous automatic train-running control [9] [10]. Without OTI, ETCS allows operation only at a maximum of Level 2, which corresponds to conventional systems in terms of line capacity.

OTI allows train detection system modules to be waived or reduced, while ETCS Level 3 allows driving at absolute braking distance. The joint application of both technologies results in capacity increases as well as cost savings. ETCS Level 3 and OTI therefore complement each other. OTI can only develop its full effect with the help of ETCS Level 3. The same applies to ETCS, which can only be operated in the Level 3 expansion stage with OTI and thus achieve the highest capacity gain compared to the status quo. It is therefore clear that a joint introduction of OTI and ETCS Level 3 is to be aimed for.

6.1.2 DAC migration

Several projects with the aim of introducing an automatic coupler in rail freight transport in Europe have failed so far, mainly because of too high costs, unclear financing as well as inadequate migration concepts [11] [12]. In recent years, there have been new projects and efforts to get back to the topic of DAC and to approach a DAC introduction once again [13] [14] [15]. Rail freight is expected to increase its capacity and play a greater role in environmentally friendly transport. The implementation of a DAC in rail freight transport plays a decisive role in the targeted capacity increase. The introduction of a DAC essentially consists of converting existing freight wagons with screw couplers to a digital, automatic centre buffer coupler.

Currently, the projects Digital Automatic Coupling in Rail Freight Traffic DAC4EU and European DAC Delivery Programme (EDDP) in particular are driving the introduction of a DAC. A new migration approach is chosen, which links the so-called “big bang” with a continuous migration. A big bang means converting all freight wagons at a defined deadline or within a few days across the entire network, regardless of their current location. A continuous migration provides for the freight wagons to be equipped with the DAC as part of their regular maintenance intervals in the depot. In this process, the screw coupler is removed and the freight wagons have only one DAC. Now the European rail sector has opted for a combination of both approaches. During regular maintenance intervals, the wagons are made DAC ready, but retain their screw couplers. On a certain date or in a narrowly limited conversion period, the DAC function can then be activated on all wagons at short notice within a few hours as part of a so-called big bang. However, this will require extensive, Europe-wide workshop capacities in a very short time. The rail operators plan to set up so-called pop-up workshops in order to be able to maintain the necessary workshop capacities throughout the countries [4] [16].

If all freight wagons of a train set are equipped with the DAC, there is a continuous electrical line that can be used for power supply and data communication. The continuous data line also enables more advanced applications such as OTI. This interdependence or complementarity is similar to the relationship between ETCS Level 3 and OTI as described in the previous section. The DAC aspect plays a role mainly for freight trains. However, passenger traffic can also benefit significantly from equipping rail freight traffic with an automatic coupler including an OTI solution. Train headway times for example, can be reduced when all trains can be operated in Level 3. The DAC offers numerous advantages for freight trains (longer trains, heavier trains, operational advantages like shorter handling times in shunting yards), but it is very cost-intensive. The costs can only be managed and justified with a significant increase in efficiency in rail freight traffic. This efficiency gain is feasible in particular with OTI and ETCS. The high costs of the DAC can be relativized if the DAC is thought of together with ETCS Level 3 and OTI. So, a joint introduction of the three technologies would be desirable from this aspect. Accordingly, three migration approaches would have to be coordinated in order to be able to use the synergies and advantages at an early stage.

6.1.3 Innovative freight wagons

New freight wagon designs offer features such as a continuous data line, which can be considered right away and do not need to be retrofitted. In addition, there are aspects such as DAC, telematics, lightweight construction, increased payload and higher speeds, which are all aimed at improving the transport and track capacity as well as throughput of rail freight.

In innovative freight wagon concepts numerous technologies are often already integrated ex works. For example:

- Electrification: continuous data and communication line (important prerequisite for OTI functionality), continuous energy supply (this makes new rail logistics services possible, such as refrigerated transports)
- Telematics: enables new applications such as predictive maintenance or remote monitoring of the load, running characteristics, location of the freight wagon or the general condition of the freight wagon
- Coupling: DAC as a standard; significantly shorter time required for train formation and shunting; higher tensile and compressive forces on the coupling allow heavier and longer freight trains and thus higher payloads per freight train
- Standardisation: uniform basic carrier wagon and flexible superstructures (more flexibility, better utilization of the basic carrier wagon)
- Lightweight construction: more payload
- Higher speed: freight wagons are designed for higher speeds, e.g. through improvements to the bogie, braking system, brake performance and brake control
- Low noise: new braking technologies and further improvements lead to lower noise emissions of freight wagons

New freight wagon types thus contribute to higher overall rail freight capacity in a similar way to DAC or ETCS Level 3. Accordingly, an innovative freight wagon design can increase the transport volume, the transported payload as well as the transport speed and thus the line capacity. This means that innovative freight wagon concepts are an ideal complement to ETCS Level 3, DAC and OTI and enhance their effects, e.g. in terms of increasing line capacity. Two projects on innovative freight wagons are e.g. SBB Cargo 5L [17] [18] and Innofreight [19]. In recent years, there have already been projects using conventional freight wagons with the aim of forming longer and heavier freight trains. Here, the necessary tractive effort was usually ensured by using double or multiple traction or a distributed arrangement of locomotives in the train set [20] [21] [22].

Alongside ETCS Level 3 and DAC, innovative freight wagon designs are thus another aspect of increasing capacity in rail freight transport. Comparable to ETCS Level 3, DAC and OTI, new freight wagon concepts are subject to certain constraints that make a rapid introduction into the market difficult (e. g. funding, allocation of costs to stakeholders, initial investment, time required for replacement of freight wagon fleet, interfaces in operation with old freight wagons, lack of long-term experience, acceptance of market participants, political framework, state support programs). This is why migration strategies are also required when introducing new freight wagon concepts.

There are already numerous projects in research for innovative freight wagon migration paths. The Competitive Freight Wagon (CFW) developed within the Fr8hub project could be mentioned here as example [23].

Similar to ETCS Level 3 and DAC, innovative freight wagons concepts can be counted as relevant surrounding migration activities, which are important in the interaction with OTI. This means that the technologies mentioned should be introduced to the market together with OTI in parallel, if possible, because they strongly complement each other. However, the initial focus of this project is on possible migration strategies for the introduction of different OTI product classes considering different market segments. A harmonized and coordinated migration path for all the above-mentioned technologies should be a subject for subsequent research projects.

6.1.4 Migration strategies in other train sectors

In the rail sector, other migration projects and migration efforts can currently be identified that face similar challenges to an OTI migration. These migration projects are already underway or are pending in the future similar to an OTI migration. For the migration projects mentioned below, it may be worthwhile to review selected migration strategies, migration solutions as well as lessons learned in followings projects and use them for a future OTI migration.

Current migration projects in the railway sector:

- Global System for Mobile Communications – Rail (GSM-R) roll-out (filling gaps in the digital rail radio network) [24]
- Future Railway Mobile Communication System (FRMCS) roll-out (replacement of GSM-R with a more powerful radio system) [25]
- Electronic interlocking roll-out (replacement of old, obsolete interlockings) [26]
- Roll-out of K- or LL-brake pads for noise reduction (noise mitigation) [27]
- Roll-out of Internet of Things (IoT) technology for freight wagons; rolling stock real-time monitoring (improve real-time capability, monitoring, cost reduction) [28]
- Roll-out of IoT technology for signals, interlockings or switches; infrastructure asset monitoring (improve real-time capability, monitoring, cost reduction) [29]
- Automatic driving ATO roll-out (Grade of Automation GoA 1-3) [30]
- Autonomous train roll-out (GoA 4) [31]
- Interlocking in the cloud roll-out (digitization of electronic interlockings) [32]
- Sensor technology for positioning roll-out (magnetic field detection, fibre optic sensing) [33]
- Sensor technology for environment perception roll-out (improvement of environment detection, e.g. for ATO) [34]
- Artificial intelligence for traffic and incident management roll-out (evaluation of complex operating situations with recommendations for action) [35]

6.2 Migration strategy for OTI

The previous section described various technologies that are also to be migrated in the rail system and that have a technological context to the OTI. The research has shown that each technology migration must fulfil specific boundary conditions that are related to the respective initial situation and the technological as well as economic situation. Since no best practice example for an OTI migration is available, an attempt was made to derive findings from the research on the migration of other technologies.

A migration can take place according to different optimization criteria and thus have different objectives. For OTI migration, also based on the findings from the previous CBA in X2Rail-2 and X2Rail-4 [1] [2], the following options were discussed:

a) Early capacity gain on highly congested lines through the ability to run in moving block,
b) Early savings of infrastructure elements that are no longer needed by shifting train integrity control to the train.

Both approaches were presented and discussed in a workshop with infrastructure managers. As a result, it was decided to pursue the second optimization criterion for the methodology development. The capacity gains possible through Moving Block, whose realisation can be optimised through clever migration, cannot be attributed to the OTI alone, but the OTI represents an enabler for this. However, since many other prerequisites must be met, such as the rollout of ETCS, the consideration of migration becomes very complex. The feedback from the infrastructure managers was that the capacity bottlenecks and need for action are well known for the existing networks and that corresponding plans are therefore in place for the rollout of ETCS and Moving Block.

On the other hand, the potential savings that result from field elements that are no longer needed and that can be optimised through clever migration strategies were considered to be relevant and can be directly attributed to the new OTI technology.

Migration according to this optimization criterion aims at the following effect:

On the one hand, costs are incurred due to the conversion of the vehicles. These are primarily based on the number of vehicles to be equipped. The timing of the investment also plays a role. There are effects from interest due to the overall migration over a longer period of time. However, these are determined by the fact that a fixed number of vehicles can be converted each year.

What can be optimised, on the other hand, is the elimination of infrastructure elements. These are characterized by the fact that they incur regular maintenance and repair costs. The sooner dismantling can take place, the sooner the savings on these annual costs begins. Over the period under consideration, therefore, there can be large differences in the total potential costs to be saved, depending on the skilful or poor choice of migration paths.

The leverage lies in the sequence of vehicles to be upgraded and in the density of infrastructure elements, which varies depending on the route. A migration path that specifically retrofits all trains traveling a certain route with many axle counters as quickly as possible realises an earlier and thus higher saving over time than a migration path that retrofits trains distributed across the network but initially does not make any axle counters obsolete at all.

At the end of all migration paths, all vehicles are converted and all obsolete field elements are removed. However, the cost-benefit ratio differs between the possible migration paths. To optimize this, the model described in chapter 8 was developed.

7 Migration of OTI product classes

This chapter describes how the OTI product classes as defined in this project are used in the market segments. First, a definition of terms is made to create a consistent understanding for subsequent work. In addition, the basic characteristics of the three OTI product classes which are relevant for the migration analysis are summarised. Following this, it is assigned, which OTI product class is to be used in the migration scenarios for which trains. Scenarios and variants are also defined for the work in the following chapters, which are then linked to migration strategies and incorporated into an optimization model.

The market segments and product classes defined in this project are considered. In addition, specific train types are selected for certain combinations of market segment and product class.

7.1 Definition of terms

In this subchapter a definition of terms is made to create a consistent understanding for subsequent work, for example, when analysing scenarios in the optimization model. It describes how the OTI product classes are used to represent the different types of trains of each market segment.

7.1.1 OTI product classes

The OTI product classes describe the different design of the OTI function in terms of three different approaches. In particular, a distinction is made between the type of communication technology, the energy supply, the type of odometry, as well as the OTI architecture itself. A very brief summary of the main differences important for the further calculation can be seen in Table 1. For further information see X2Rail2-WP4-D.4.2 [36].

Table 1: OTI product classes and their architecture, technology and train integrity criteria [37]

Product class	OTI architecture	Technology	Train integrity criteria
1	head + tail	Wired communication network (e.g. Ethernet).	Communication liveliness between head and tail
2	head + tail	Wireless communication network, kinematic sensors (e.g. speed from ETCS wheel sensors)	verifying train tail coherent movement with respect to the front cabin
3	head + every waggon	Wireless communication, separation detection sensors (e.g. RSSI, IMU, GPS sensors fusion)	detecting separation between adjacent waggons

7.1.2 Train types

The train types describe the composition, characteristics and type of train within a market segment. Although there are several parameters possible to subdivide between train types (e.g. weight, wagon type, payload etc.), the proposed distinction is made according to the OTI product classes as the focus lies on the cost of retrofitting each train type. When using an increase in capacity as the optimization criterion for the model, train parameters such as speed and length of the trains become relevant as well.

In the area of freight transport, different types of freight trains are in use, e.g. block trains or mixed freight trains. In regional traffic, there are fast trains, but also slower trains on branch lines. In the high-speed market segment, a distinction can be made between very fast passenger trains (over 250 km/h) and long-distance trains, which tend to serve areas away from major cities (160-200 km/h). The various train types differ overall, for example, in terms of train length, train formation, maximum speed, driving dynamics, or passenger or freight capacity.

For the market segment high-speed one model train is used which will be equipped with product class 1, for the market segment Regional two model trains are defined, one with wired communication ability which will be equipped with product class 1 and one without this possibility which will be equipped with product class 2.

The market segment Urban/suburban will not be considered as OTI is already common practice in this market segment and thus no migration strategy is needed here [38].

For the market segment Freight, a distinction will be made between block trains and single wagon trains. In the calculations the market share of both is split in half. For the economic analysis for block trains product class 2 is assumed and for the single wagon train product class 3.

Determination of the train types for the optimization model:

- Intercity high-speed
    - I1: Very fast high-speed train (300 km/h)
- Regional
    - R1: Regional express train (high capacity, 160 km/h)
    - R3: legacy Regional train (short length, below 100 km/h)
- Freight
    - F1: Block train, medium weight and medium length (e. g. container shuttle, 100 - 140 km/h)
    - F4: single wagonload transport (100 km/h)

The following Figure 2 shows an overview of the terms defined above and brings the individual aspects together in one representation. This makes it clear which parameters and combinations result in the individual scenarios.

Market segment / Product class	Intercity high-speed	Regional	Urban-suburban	Freight
Product Class 1	Train type I1	Train type R1	See Regional	
Product Class 2		Train type R3		Train type F1
Product Class 3				Train type F4

Figure 2: Assignment of train types to product classes depending on market segment

7.2 Scenario description

A scenario in this report is defined through its length of the migration process. In accordance with the assumptions made in the DAC report [11] as well as expert discussions within a dedicated Infrastructure Manager (IM) workshop within the X2Rail-4 work package, the workshop capacities are assumed to be sufficient once the migration path has been chosen and decided upon. Therefore, this report aims to analyse what monetary effects different migration periods would have.

The migration periods analysed have been set to match the maintenance intervals of each train category. As the retrofitting of the freight trains is the most complex part, this parameter has been varied.

The following maintenance intervals and thus durations for the migration paths have been assumed:

- Intercity high-speed: 2 years
- Regional: 4 years
- Freight: 6/8 years

The assumed migration period means that at the end of the period all trains concerned will have an OTI function, i.e. for example for intercity high-speed trains at the latest two years after the start of the migration process.

For high-speed trains a migration period of two years is assumed. This assumption is made mainly for the reason that this type of train needs to be maintained and inspected in the depot significantly more often than other types of trains. On the one hand, high-speed trains have significantly higher mileage in a short time, and on the other hand there are increased safety requirements due to the significantly higher speeds during operation. For these reasons, among others, high-speed trains are subject to closer maintenance. The tight maintenance intervals for high-speed trains facilitate migration of the OTI function. Such trains already have the necessary technical requirements, such as a train bus or a continuous electrical data and communication link throughout the entire train. Often, all that is required to implement the OTI function is a software adaptation and a correspondingly adapted vehicle approval. Compared to the other market segments, OTI migration for high-speed vehicles can be implemented with relatively little effort and in a short time.

Regional trains also have a high mileage and must therefore be maintained at short to medium intervals. Similar to high-speed trains, the majority of regional trains already have the basic technical equipment for upgrading to an OTI function (train bus or a continuous electrical data and communication link throughout the entire train). Since the maximum speeds in regional traffic are significantly lower than in high-speed traffic, it is assumed that corresponding high-speed safety-related shorter maintenance intervals are not required in regional traffic and that fewer depot stops are necessary. However, this reduces the time availability of the regional vehicles in the depot and the OTI migration period is accordingly assumed to be four years.

In contrast to high-speed and regional trains, equipping freight wagons with OTI is much more complex in terms of time and installation. The mileage of freight wagons can be significantly lower in a comparable period than in high-speed and regional traffic. Special freight wagon designs in particular have very low operating times and mileages. Due to the rather simple technical equipment and the lower mileage in relation to the period, the maintenance interval for freight wagons can be significantly extended. This means that freight wagons are only treated in the workshop at very long intervals, i.e. they are rarely in the depot (regular maintenance interval is six years [39]). In addition, the maintenance intervals and workshop visits for freight wagons are usually extended to the maximum periods (extension up to eight years is possible [39]). Due to the rather simple technical equipment of freight wagons, extensive modification work is required on the wagons to implement an OTI function, in contrast to high-speed and regional passenger trains. In this market segment the greatest conversion effort is required, since many freight wagons do not yet have the necessary basic equipment for OTI (e.g., power supply on the wagon, continuous electrical and communication data line, etc.). Due to the special boundary conditions for the OTI migration of freight wagons, two different migration periods are assumed (6 years regular maintenance interval, 8 years regular renewal option; see Table 2). Because the migration periods for the high-speed and regional trains remain the same in all scenarios, there are two different scenarios for the migration model set up in the following chapter 8. Subsequently, the calculated scenarios are compared and evaluated in detail in chapter 9. In addition, a reference scenario is considered as well. The reference scenario assumes that the OTI technology is not rolled out and the train integrity will be monitored by the infrastructure assets. This is solely done for the purpose of the economic analysis to be able to compare the cost in the two migration scenarios to the current state.

Table 2: Determination of OTI migration periods depending on scenario and market segment

Market segment	Reference Scenario	Scenario 1	Scenario 2
High-speed	---	2 years	2 years
Regional	---	4 years	4 years
Freight	---	6 years	8 years

7.3 Study area

For the optimization of a migration, the consideration of a network is necessary, since it is important to select the sequence of trains to be converted in such a way that as many infrastructure elements as possible can be removed as early as possible, depending on the routes travelled. Pure corridors as e.g. the System Platform Demonstrator (SPD) defined for Shift2Rail, which serve to demonstrate the application of the developed technical demonstrator (TD), are unsuitable as a study area for a migration, since their conversion strategy would be trivial. This study only makes sense, if there is more than one route.

Selecting a representative network and the associated operating program has proven difficult. On the one hand, the size of the network must be manageable, i.e. it must be possible to model it with reasonable effort and on the other hand, it must be computable for optimization algorithms with existing computer capacities in an acceptable time.

The selection of a sub-network from a real existing network such as the European rail network has not proven to be effective. On the one hand, the network should be equally representative of all Shift2Rail partners, which would not have been the case with a partial selection from the TEN, for example. On the other hand, the availability of the required data of the infrastructure and especially of the operating program and the vehicles used is not given. The data could not be provided by the project partners in the required form, scope and time.

Therefore, the approach of an artificial study area was chosen, which is based on a real network and operating program and serves the purpose of demonstrating the optimization of migration strategies developed in the project.

In order to identify a suitable field of application for the methodology described in the section above, the following factors were considered: calculation time and resemblance to a European country with mixed-traffic lines for reasons of closeness to reality. As the processing time for calculating optimised migration paths should not be too long, very large and complex networks (as for example the networks of Germany, France or cross-border scenarios) had to be avoided. With Austria a smaller country was chosen as the basis of the model. Publicly available infrastructure and network operation data on the basis of node-edge-relations was implemented as a first step [40]. As data contained very different levels of detail, the network was further processed in order to reduce complexity within major nodes by means of systemic aggregation. Moreover, train counts were algorithmically calculated as described in chapter 8.3.1. Line categories were assumed based on train counts and accumulated length of edges. Trackside field elements (axle counters) have been integrated within ranges based on Germany regulations for infrastructure [41].

For these reasons, the resulting network and operational program has been systematically alienated and can be referred to as an artificial network resembling Austria. With this study focusing on the methodological approach described above it does not have the objective of creating detailed recommended actions for specific networks or countries, but rather centres upon systemic behaviour.

The network consists of 87 nodes and 94 edges which has proven to be the maximum manageable size for existing computer capacity and time available.

If data on network parameters as well as an operational programme for passenger and freight trains is available, the methodology can easily be transferred and applied to a real-world scenario.

8 Development of migration paths using an optimization model

8.1 Transfer of the migration strategies to an optimization model

Different OTI migration strategies focus on different KPI while trying to derive a fitting set of actions in order to achieve the migration target (mostly full migration). Speaking in terms of quantitative modelling and optimization, these parameters can be referred to as objective criteria. Amongst others, early capacity gains or overall cost reduction can be named as examples. Alternatively, isolated operational parts of a network can be prioritised to maximise effects. These objective criteria can, but do not necessarily have to, be conflicting.

The idea behind quantifying a migration process is to identify the order of system elements to be migrated in such manner as to optimise a certain objective criterion. In regard to the OTI migration, the aspired quantified outcome is which train to equip with which kind of OTI technology at what time while satisfying the required strategy (and thus objective criterion) in the best possible way.

Expert workshops within the project revealed special interest and focus on the possibility of removing infrastructure elements such as axle counters to reduce costs. Once all trains running over a line are equipped with OTI technology these elements can be removed as they are not needed anymore. Thus, costs for these infrastructure elements can be reduced as they do not require maintenance or reinvest cost anymore. As trains run within a network are highly complex and intertwined the question which trains to equip first to save money as early as possible is a suitable case of application for mathematical optimization modelling where costs over time pose the objective.

8.2 Methodology of the model

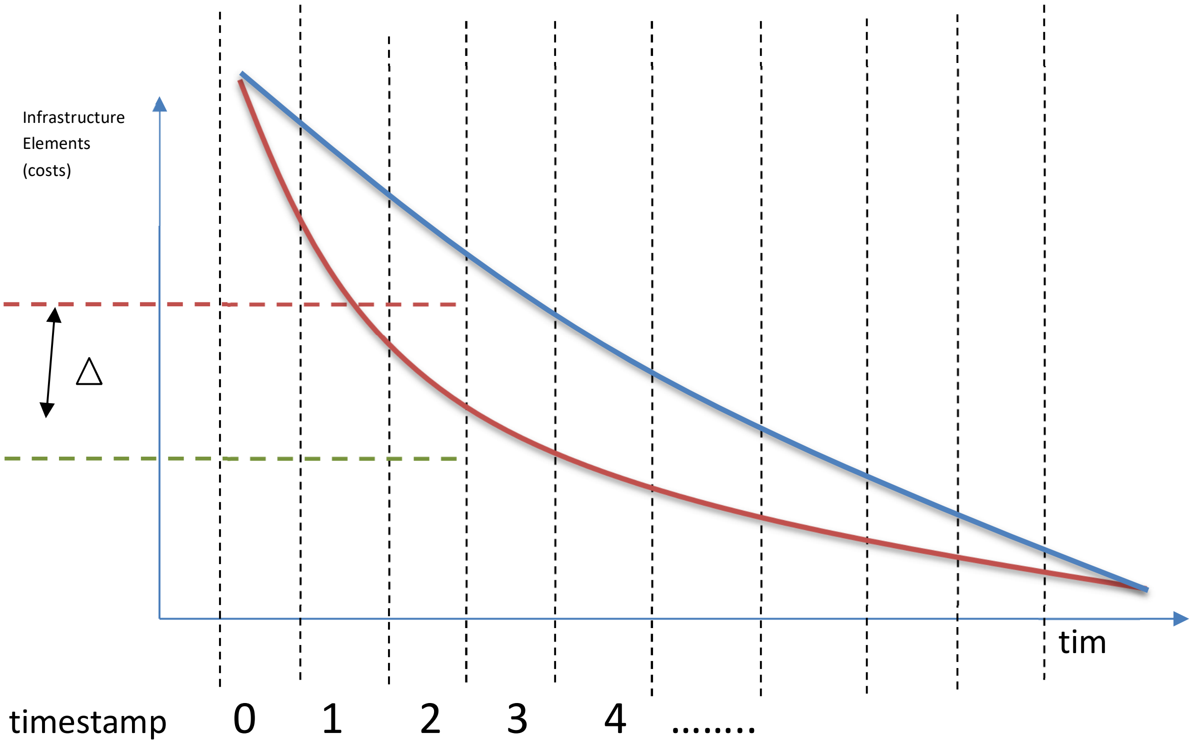

Figure 3:simplified and exemplified plot: costs over time for a generic track infrastructure during OTI migration process

Figure 3 shows two generic examples of reducing costs over time by equipping trains with OTI technology where the blue curve stands for an unoptimized OTI migration and the red curve for the expected optimised case. Please note that the figure is only meant to contribute to a better general understanding of the described research problem and does not claim to being accurate or correct. This does not only refer to the gradients of the curves depicted but also to their monotony. The figure shows two plots both of which have the same amount of infrastructure elements to start with and end (see assumptions above). However, the red curve descends more steeply within the first part of the observation period - and thus represents higher cost savings in comparison to the blue curve. By calculating the according Δ for each time stamp, it becomes clear that by cumulating the capacity levels over the timestamps, an objective function as follows can be created:

$$\min \sum_{e \in E} \sum_{t=t_0} c_{te}$$

Where the network´s state is described at a certain timestamp $t \in T:=\{t_0,\ldots,t_N\}$, where $t_i:=i^*\backslash \Delta T$ (e.g. one year), *e* is a certain edge within the amount of the infrastructure´s edges *E* and *c* is the amount of infrastructure elements of a certain edge *e* at a certain timestamp *t*.

The amount of infrastructure elements *c* of a certain edge *e* has a semi-binary state as it is assumed it can be either the initial amount or 0, dependent on the number of trains equipped with OTI technology running over it. Hence the network, the operation program, timetables and train routes function as input to the optimization problem. Moreover, the observation period has to be defined as input as well.

Variables within the optimization problem can be defined as follows: assuming that sooner or later every train will be equipped with OTI technology, every train has a distinct timestamp marking its upgrade with OTI (for example, in year 2). As the OTI status of a train has indirect impact on the capacity of the edges it is running over, the timestamps of the OTI upgrade of trains can be varied within the optimization problem und thus an optimal order of equipping trains with OTI identified. In a mathematical sense, this leads to variables defined as follows:

- $o_{tn} \in \{0,1\}$ *being the binary status of OTI-equipment of train n at timestamp t*

It is assumed that for passenger and freight block trains only complete trains can be equipped and thus its status can be described by a binary value. In contrast, single wagon load freight trains have to be modelled on a deeper level, so the binary status is applied to single wagons.

Further constraints include equipped trains/wagons stay equipped and assure that the sum of equipped trains per year is equal to the defined equipment rate per year.

8.3 Use case and results

8.3.1 Definition and application of the use case

The derivation of the generic network and operating program is described in detail in chapter 7.3.

Figure 4 shows the resulting network and how many infrastructure elements the according edges have.

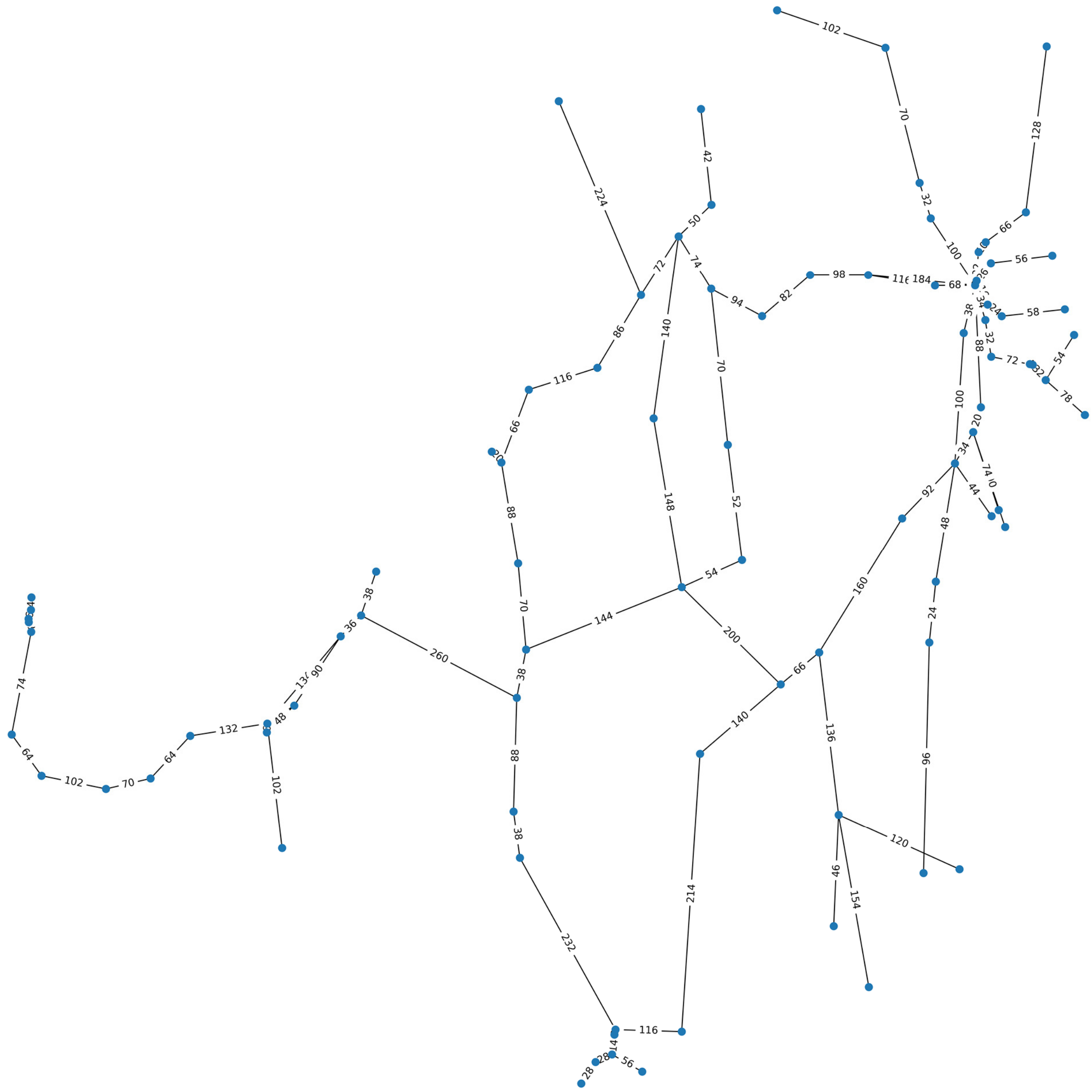

Figure 4: Network with amount of infrastructure elements

The network is characterised by one major junction station and several smaller junctions. Moreover, mixed-traffic is assumed (as for example is the case in Germany, Switzerland or Austria) which means that different train categories share the same infrastructure. The train categories were defined as described in chapter 7.1.

Table 3: train types used in the model

train_name	train_type
I1	High Speed long-distance
R1	Regional short-distance
F1	Freight block train
F4	Freight single-wagon load
R3	Regional short-distance

For every edge, train counts were assumed based on realistic numbers. These were further algorithmically calculated to train rides with specific routes (several hundred distinct routes) by the means of the SUMO dfrouter tool [42]. The resulting train rides were then further converted to the amount of physical trains on the basis of assumed train cycles. As described above, for the freight sector block trains and single wagons were divided (assuming that half of the counted freight trains were block trains). The resulting physical train amounts can be seen Table 4:

Table 4: train amounts

Train category	Amount	entity
I1	46	Trains
R1	15	Trains
R3	16	Trains
F1	261	Trains
F4	13488	wagons

Based on the described input an array of variables was defined as described in Table 5:

Table 5: array of variables

	Train 1	Train 2	…	Train x
Year 1	t_11	t_12		
Year 2	t_21	t_22		
…				
Year y				t_yx

The variables are defined for wagons likewise and are binary variables, stating whether or not a certain train/wagon is equipped with OTI in a certain year.

The amount of infrastructure elements can then be calculated with an if statement: if all trains in a certain year running over an edge are equipped with OTI (and thus all the variables of these trains are 1), the amount of infrastructure elements can be reduced from its initial number to 0 in this year. Summing up the infrastructure element amounts of all edges for a certain year leads to the network sum of infrastructure elements. By summing up these over the years, the optimization objective is defined. By minimising this final sum, trains will be equipped at a certain time as to optimally (meaning as early as possible) reduce the amount of infrastructure elements.

The result highly depends on the equipment rate assigned to each train category, meaning how many trains/wagons can be equipped in a certain time span. This was analysed in two different scenarios as shown in Table 6:

Table 6: definition of scenarios (equipment time in years)

Train category	Scenario 1	Scenario 2
I1	2	2
R1	4	4
F1	6	8
F4	6	8
R3	4	4

It is assumed that within a defined timespan all trains of a certain category can be equipped. Table 6 shows that in Scenario 1, timespans were defined according to established revision cycles of trains, assuming that once they are in a workshop for regular inspection they can be retrofitted with the OTI technology. As the far majority of units to be equipped are freight trains/wagons, the time needed to do so is varied between the scenarios.

8.3.2 Results

The variables, constraints and objective of the optimization model have been created and implemented into Python development language. The Python Gekko [43] NLMIP library was used as a development environment. APOPT was used as a solver. Calculation time varied from ~6 h for Scenario 1 up to ~ 12 h for Scenario 2.

Results of the use case described above are shown in Figure 5:

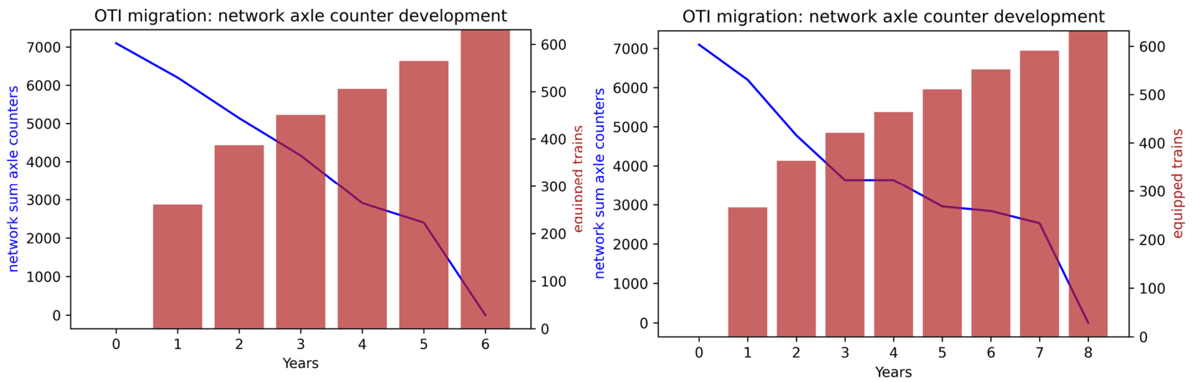

Figure 5: network sum of axle counters and equipped trains for scenario 1 (left) and scenario 2 (right)

The blue line characterizes the development of the network-wide number of axle counters for the two scenarios respectively. In general, both scenarios behave very similarly: While the number decreases quite linearly in the first years, a (slightly) flattening course - followed by an even steeper fall, resembling an “S” - to the end of the observation period can be observed for both scenarios. The results show that by optimising the order of train equipment, axle counters can already be removed in the very first years, despite only few trains in the network being equipped (a random equipment of trains might possibly rather resemble a negative exponential behaviour, with few gains in the beginning – as the rate of equipped trains is still very low – and high gains to the end). The flattening section in the mid-years is slightly longer in Scenario 2, as equipment rates are lower.

The described trend is also influenced by the number of equipped trains in the network shown by the red bars. As shown in Table 6, it is assumed that high speed passenger trains are fully equipped within the first two years. For this reason, the share of equipped trains in both scenarios rises steeply within the first two years and flattens later on, as within four years all regional trains are equipped and to the end only freight trains and wagons are still equipped (for Scenario 1). The respective proportions of Scenario 2 are shown in Figure 6 for block train categories (single wagons were also calculated but not included in the figure for visualization purposes).

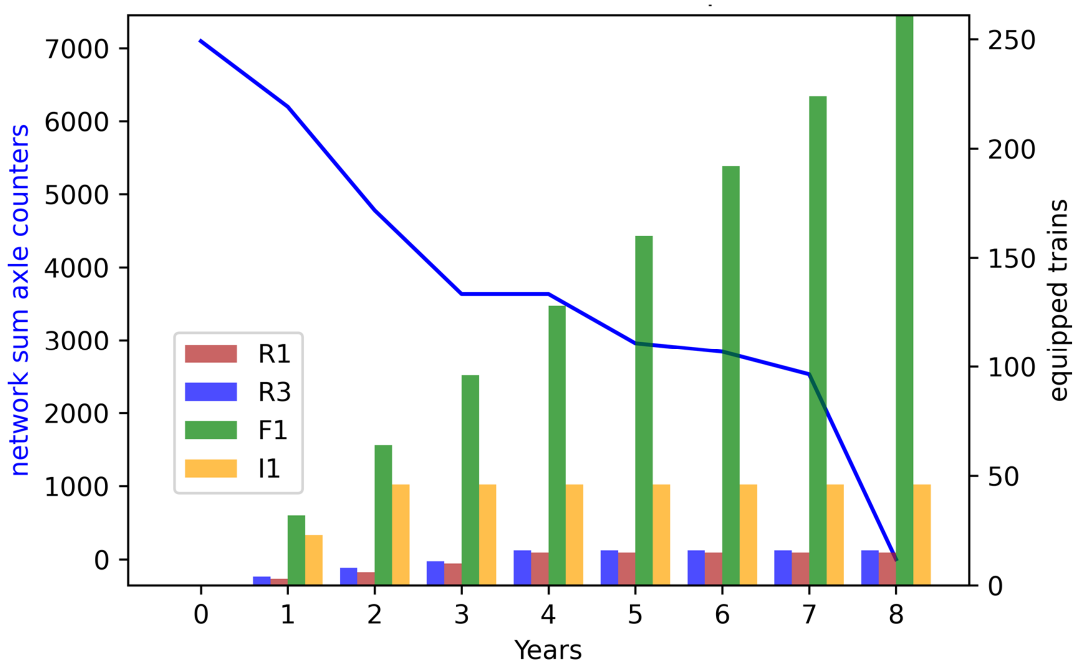

Figure 6: network axle counter development for block trains (Scenario 2)

The steep fall in the last year can be explained by the large effect of all trains being equipped. It can be further seen that freight trains have a large influence on migration strategies as their share of the operational program is considerable. Furthermore, they tend to have longer routes than passenger trains.

Figure 7 shows where exactly in the network the axle counters are removed by example of Scenario 1.

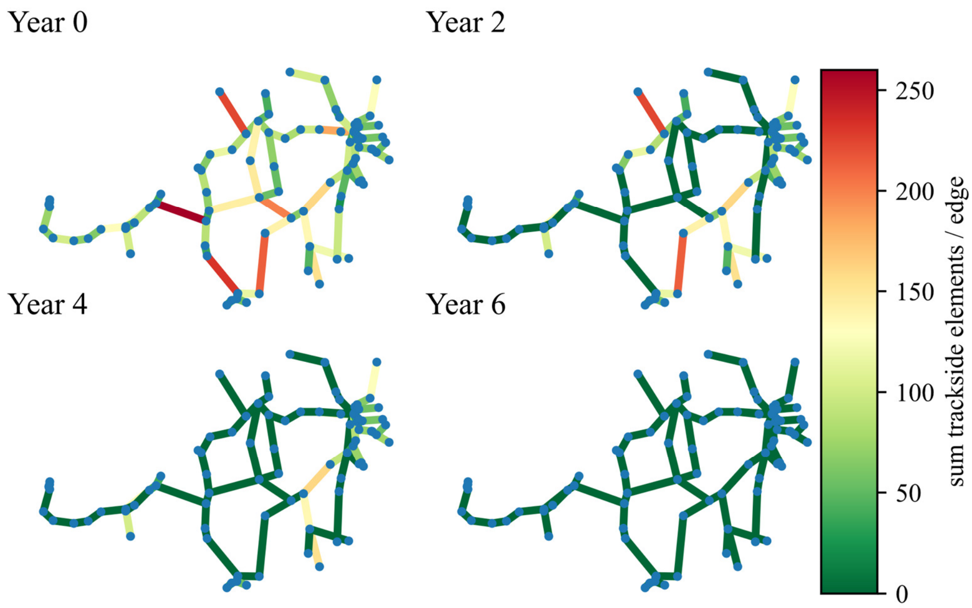

Figure 7: Network-wide development of axle counter numbers over years for scenario 1

Here the colouring of edges refers to the amount of axle counters that are “active” on a certain edge, with red shades standing for high numbers and green for low numbers. It can be seen that the share of green rises over the years, with all trains -and thus the network- being fully equipped in year 6. Which axle counters exactly are removed in the first years depends on both the routes of trains running over it as well as how many axle counter the edge has.

9 Economic analysis

The following chapter describes the analysis of the optimization results with regards to their economic effects of different migration paths on the life cycle cost and the consecutive implications for the stakeholders.

It is demonstrated that a methodology has been developed and applied as an example. It is however based on assumptions. In particular, cost assumptions on the OTIs were already not published in X2R-2 because industry partners vetoed them due to compliance issues.

The results apply to a generic application and are only as realistic as the assumptions made. If, however real data are provided on the technology and a use case, the optimization model is able to calculate out ideal migration paths.

9.1 Input and methodology

As input for the economic analysis we have the output of the optimization model. This is provided in form of excel files one for the trackside infrastructure and one for the OTI integrity. For each scenario information are provided of how many axle counter per year can be removed and how many trains are fitted with OTI. The axle counter can only be removed and thus cost be saved in the year after all the trains running on a line have been fitted with OTI.

The capital and operational costs as well as life span and interest rate used for the economic analysis are the same as have been used within the cost benefit analysis of X2Rail-2 and X2Rail-4 [1] [2]. Depending on the product class, cost values have been used for the OTI master, the communication and the OTI slave.

Table 7: Cost components for OTI

			Product classes					
			1	2	2	3	3	unit
			research, development and safety approval cost					
train	OTI master	module	X	X	X	X	X	per train
		dashboard	X	X	X	X	X	per train
	communication	wired	X					per train metre
		wireless		X	X	X	X	per train
	OTI slave	end of train module for passenger trains		X				per train
		end of train module for freight trains			X			per train
		module wireless				X		per wagon
		energy harvest + module wireless					X	per wagon

In addition, the train characteristics number of driver cabins and length had to be considered to determine cost for wired communication, the number of OTI master modules and dashboards to be installed as well as the number of freight wagons if applicable to determine the costs for product class 3. A brief characteristic of the train types used can be found in chapter 7.1.

A life cycle cost analysis has been performed for retrofitting each train type over the course their respective maintenance cycle (2 years for High Speed, 4 years for Regional trains and 6/8 years for freight trains). The analysis only considers the retrofitting costs to equip the trains with OTI as well as replacement costs of OTI technology within the chosen assessment period. This assessment period of 30 years is a common period for assessment in railway infrastructure. However, the cost elements as well as life span of all parts of each train type outside of OTI have not been considered as they are assumed to be identical in the baseline as well as all analysed scenarios.

Figure 8 shows the life cycle cost for each train type for Scenario 2. The figure visualises the initial capital costs for retrofitting the different train types and the lower costs when only operational expenditure occurs. For the passenger trains the life span for all cost components is 20 years. For the freight trains however, there are cost components with a shorter life span of 6 years therefore costs in the form of reinvest can be seen.

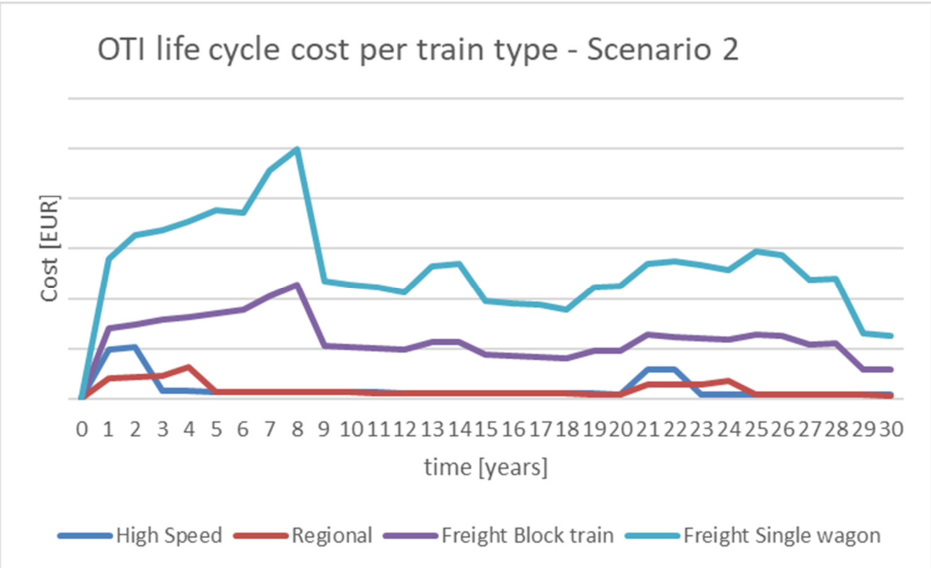

Figure 8: OTI life cycle cost per train type - Scenario 2

9.2 Life cycle cost analysis

A life cycle cost analysis has been done for the two different migration paths as well as for a reference scenario.

The reference scenario assumes that no investment for OTI is done and the status quo on the infrastructure side remains. This is done to show after what period of time the investment for the

OTI technology are compensated by the reduction of costs through the elimination of new investment cost for trackside infrastructure and their continuous operational costs (break-even). Figure 9 below shows that this is the case after around 13 years.

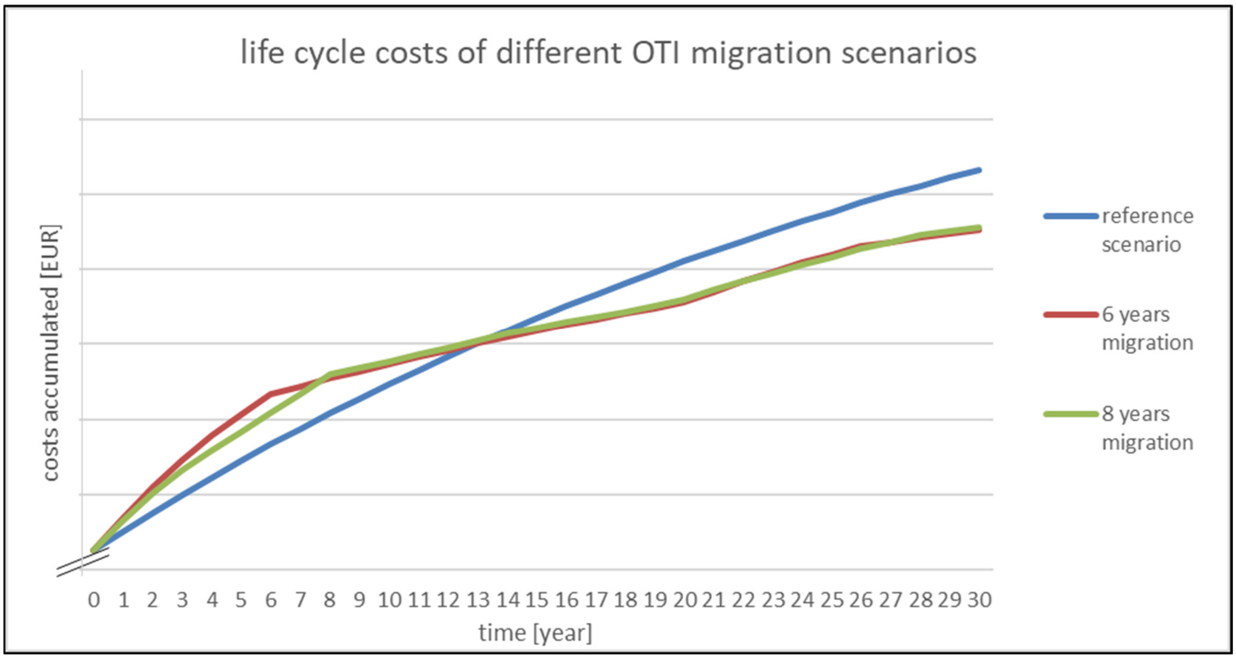

Figure 9: Life cycle costs for different OTI migration scenarios

The figure shows that the cost for Scenario 1 is of course the highest in the beginning as the investment for retrofitting the trains with OTI have to be done in the shortest amount of time and thus a higher share of the cost occurs early on. However, with equipping the trains over a short period of time, also the infrastructure elements can be reduced early, this means that cost savings in this scenario occur sooner than in the other scenario.

After 30 years the accumulated, discounted costs in Scenario 1 are 15% less than in the reference scenario. There is however not a huge difference between the life cycle costs of Scenario 1 and the Scenario 2 (< 1%).

9.3 Sensitivity analysis

As the number of axle counters that shall remain on the infrastructure for back up purposes will be decided upon by each IM a sensitivity analysis has been performed on the amount of axle counter which will be removed on the example of Scenario. In this example the break-even point of removing all axle counter or keeping the status quo is after ~13 years. Meaning that from a cost perspective after 13 years Scenario1 becomes cheaper than keeping the status quo. When 10% or 20% of the axle counter will be removed this break-even point is after 16 or 30 years respectively. For 50% remaining axle counter there is no break-even point with the reference scenario within the 30 years analysed.

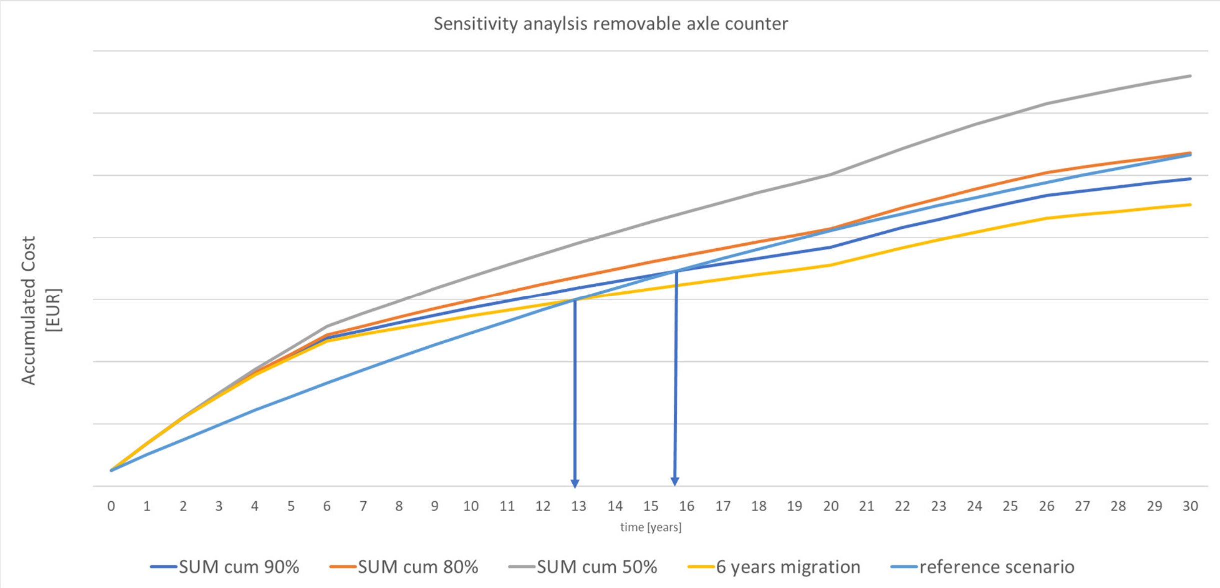

Figure 10: Sensitivity analysis for different shares of axle counters removed (Scenario 1)

9.4 Effects of the migration paths for the different stakeholders

Retrofitting trains with OTI creates investment as well as operational costs for the RU and wagon owner. The removal of trackside infrastructure on the other hand reduces the cost over time for the IM. Hence, the cost and benefits do not occur for the same institution. Therefore, a way forward has to be found to solve this situation. This is however not part of the tasks in this WP. The aim of this report is to calculate, visualise and analyse the costs for each stakeholder.

Figure 11 visualises the yearly costs per stakeholder on the example of the 6-year migration path. It can be seen that high costs for the RU/wagon owner occur in the first 6 years as during this period all trains are equipped with OTI technology. In the following years the costs are lower as only operational costs occur before they rise again after 20 years when part of the OTI equipment needs to be refurbished. A general decrease can be seen due to the discounting approach applied. In contrast the cost for the IM decrease over the first seven years as more and more trains are equipped with OTI technology and thus trackside infrastructure for train detection can be dismantled.

In Scenario 1 the yearly costs for the RU/wagon owner exceed the costs of the IM after 3 years (see Figure 11). The accumulated cost of the RU however only exceeds that of the IM in this scenario after 6 years, so right after the full migration (see Figure 12).

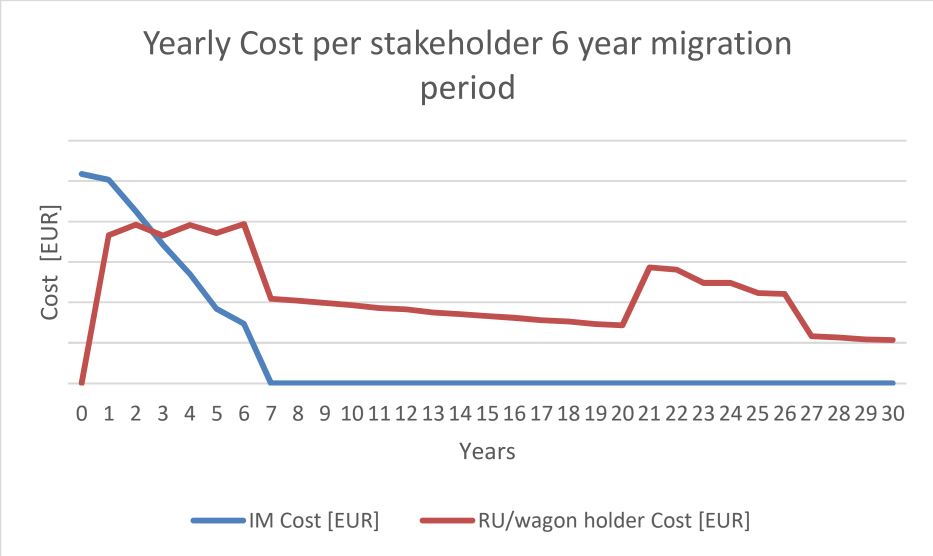

Figure 11: Yearly costs per stakeholder - 6-year migration period

Figure 12 shows the accumulated cost in both scenarios for each stakeholder. It visualises quite well the difference of each migration path for the stakeholder. For the RU/wagon owner the accumulated costs are higher in Scenario 1, when the migration in done over a shorter time. The accumulated costs for the IM are higher in Scenario 2 when the infrastructure elements have to remain in the field and be maintained for a longer time. For the total system however, the difference between these two scenarios is only marginal with 0,4% (compare Figure 9).

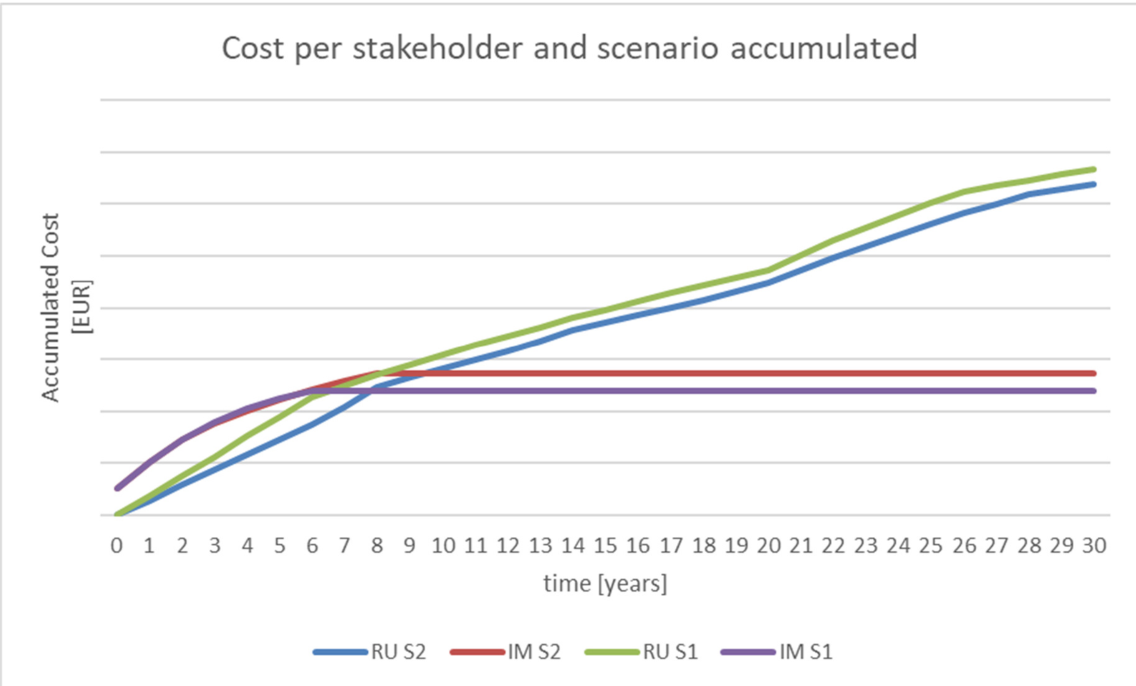

Figure 12: Accumulated cost per stakeholder and scenario

9.5 Further implications for the CBA performed in X2Rail-2 and X2Rail-4

Transfer of the results

The main difference of the calculations performed in the migration analysis and the cost benefit analysis is that the cost benefit analysis has been performed on a real line. The migration analysis however had to be performed on a network as an optimization problem on a line would not show any effects.

In the CBA these costs are assumed to all occur at one point in time. With the results of the migration analysis, it can now be calculated in more detail when exactly the costs occur for which line. This does however depend on the network for which the results are calculated. For the individual line analysed in X2Rail-2 and X2Rail-4 however the timestamp of removing the axle counter would be the same for all of them as they are all on one line.

The results obtained in this analysis can therefore not be simply transferred to the calculations done in the CBA.

Train length determination

The train length determination was not originally included in X2R-2 and was subsequently added by an amendment. The approval for this came so late in the project that this additional functionality could no longer be considered in the CBA carried out there and should therefore be taken up again in X2R-4.

Since this content extension has made the safe train length determination de facto part of the OTI and is therefore technologically and functionally connected, there are no effects on the migration optimization carried out, so the train length determination has not been considered separately.

With regards to the cost estimates for the OTI no changes have been made either to include the functionality. For reasons of competition, no information from the manufacturers could explicitly be provided in the project on the costs for the OTI – and thus also the determination of the train length. Therefore, the costs for the initial OTI were estimated on the basis of comparable technologies and expert knowledge. The resulting possible inaccuracy does not justify any refinement of the values due to the addition of the additional functionality of determining train length, especially since it is assumed that this should not lead to any significant increase compared to the previous cost assumption as no additional hardware is expected.

10 Conclusions

The aim of the studies on migration for OTI was to show under what conditions the new technology can be rolled out and where there are opportunities for optimization. The focus was on the three OTI product classes and their possible applications in the various market segments.

The migration of a new technology must always be considered in the context of the related constraints and surrounding technologies and developments to be carried out optimally. It must also be taken into account that the optimization criteria can be in competition with each other for an optimization.

In the present example of the migration of the OTI, the technologies DAC, ETCS and innovative freight wagons were identified as being closely related in this context. However, due to the complexity and the available information on the different development statuses, it was impossible to include these in an integrated migration consideration. Therefore, this project focused on the OTI and modeled it generically. The consideration of the boundary conditions going beyond this must take place in the context of the real rollout under the then prevailing conditions. The methodology developed provides a good starting point for this.

Based on the assessments of the experts in the project, the savings potential through the dismantling of axle counters and track circuits that were no longer required was defined as an optimization criterion. The potential for optimization lies in the fact that if the trains are optimally equipped with OTI, sections of track can be operated without axle counters as early as possible without restricting the operating program. If this is done successfully, cost advantages arise for the infrastructure operator through dismantling the axle counters as early as possible, because there are no longer any costs for maintenance, repair or reinvestment for these infrastructure elements. This is particularly effective for routes with low density of traffic and a high number of infrastructure elements.

On the other hand, there are the costs for equipping the trains. These have to be paid by the wagon owner. For the shifting effects resulting from the introduction of OTI, balancing mechanisms must therefore be defined within the ecosystem in to compensate for the costs to be paid for by one party and the costs saved by the other party, so that an efficiency gain can be achieved for the entire railway system, such as it could be shown in the economic analysis.

Methodologically, an optimization model was newly developed for this project, which deals with the optimization criterion and the defined constraints and performs a mathematical optimization of the possible migration paths. This model was applied prototypically for the first time to a generic network with an operating program. The results show the potential of an optimization under the given input variables.

Due to data availability and representativeness of a network and fleet selection, no application to a real network could be done in the project. For subsequent projects, however, a tool is available with the developed computation model, with which optimised migration strategies can be determined, given the appropriate data input. This is, however, not in the scope of this project.

Likewise, there is potential for scientific follow-up to further develop and optimise the tool on the one hand and to make comparisons between the optimised results and, for example, non-optimised (random) migration processes or manually performed optimizations on the other hand. In this way, for example, migration plans drawn up with human expertise can be reviewed and compared to computational results.

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Appendix A: Ownership of results

The following Table 8 lists the ownership of results for this deliverable.

Ownership of results			
Company	**Percentage**	**Short Description of share/ of delivered input**	**Concrete Result (where applicable)**
DLR	100%	Development of methodology and tool, gathering of data input and economic analysis	Optimised migration paths, economic evaluation

Table 8: Ownership of results