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D19.1

Life Cycle Cost and benefits inputs for CBA – Phase 1

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Please note that this document is currently a draft version. It is subject to change and further updates will follow as more information becomes available or additional revisions are made. Readers are advised to consult the latest version to ensure they have the most up-to-date information.

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2 Executive Summary

This document constitutes "Deliverable D19.1: LCC and Benefits Inputs to CBA Phase 1" of ERJU Flagship Area 5 project FP5-TRANS4M-R. This document reports results from Task 19.1.

The objective of this report is to provide inputs on costs and benefits for the EDDP CBA work package as described in the Grant Agreement.

It focuses mainly on costs related to the:

- migration phase: transport costs and Installation costs
- utilisation phase: acquisition and maintenance costs
- disposal phase

All those costs were estimated thanks to hypotheses based on inputs provided by various stakeholders.

The deliverable also includes in appendix 8.1 the work done on the 2 e-couplers prototypes to support the decision-making process between these 2 prototypes (Appendix 8.1).

To ensure confidentiality to handle these sensitive data, the works mentioned above have been carried out by a subcontractor, IKOS Consulting.

The costs assessment has the following limitations:

- quality of the data, temporal scope of the projections, and necessary arbitrations in case of conflicting data;
- uncertainties related to design, manufacturing, component costs, and operational behaviours coming from the current pre-industrialization phase
- assumptions for the migration phase based on current data, with uncertainties regarding planning, number of production sites, and installation costs only estimated for wagons equipped with the UIC space[1].

In analysing all the results, a rough estimation of the life cycle cost of the DAC was established. At the current stage of the project, the goal of this assessment is to provide an indicative trend rather than a definitive estimate.

DAC Migration Costs	Supply Costs	• Estimated cost in euros for transporting each DAC unit according to the favored EDDP deployment scenario: **26 € per DAC meaning 52 € per equipped wagon**[2]

[1] The UIC space is the place reserved to the installation of the draft gear part of the DAC under the frame of the wagon

[2] For around 400 000 wagons equipped in 4 years

	Installation Costs	• Total installation cost for a wagon with UIC-installation space, Type: vertical support, 2 Axles: **2 012 €** • Total installation cost for a wagon with UIC-installation space, Type: vertical support, 4 Axles: **2 111 €**
DAC acquisition and utilisation costs	Acquisition costs	• Average acquisition cost for the wagon DAC (including scaling factor): **11 014 € / coupler** • Average acquisition cost for the wagon On Board Unit (including scaling factor): **8 064 € / wagon** • Average acquisition cost for the locomotive hybrid coupler (including scaling factor): **30 831 € / hybrid coupler** • Average acquisition cost for the locomotive On Board Unit , without the unit power supply system (including scaling factor): **9 783 € / locomotive**
	Maintenance costs (for a 30 years lifespan)	• The cumulative cost for the DAC is **364 € / year** (224 €/year for spare parts, 110 €/year for human resources, and 30 €/year for corrective maintenance) • The cumulative cost for the OBU per vehicle is **319 € / year** (266 €/year for spare parts, 23 €/year for human resources, and 30 €/year for corrective maintenance) Some provided operations are synchronized with overhaul inspection of the wagons to avoid additional shipments and downtime costs
	Disposal benefits	• The end-of-life recycling of a FDFT system could yield a **benefit of over 300 €/wagon**, excluding battery resale.
Capacity Benefits in Yards		• **The automation and digitalization of train operations brought by the FDFT system , especially by FDFT system level 5 allow a faster handling of the trains in Marshalling Yard than the current screw coupler system.** This leads to a significant increase of the number of trains handled on the MY infrastructure in a given timespan (10 hours in the shown analysis). **The**

	gains are between 30 and 75%, depending on the train length and the part of the MY considered.

The costs presented are based on assumptions detailed in the main text. It is important to highlight that for acquisition and maintenance costs, the maturity level is significantly higher for the DAC component, particularly for wagons, compared to the OBU components. The lack of maturity of the OBU results in significant variances in the acquisition costs provided by manufacturers and poses challenges in accurately detailing the costs.

As the lack of maturity is even higher at this stage of the project for the locomotives , it has not been possible yet to assess the costs of the energy supply system and the installation costs.

In this report, the approach of the benefits allowed by the FDFT system implementation is limited to capacity gains in the Marshalling Yards. The Swedish university KTH has conducted a study showing that FDFT system increases the number of trains that can be handled in the different parts of a MY from 25% to 75% in comparison with the current UIC manual coupling system. This improvement of the wagon processing may speed up the transit time of the wagons in MY and support the foreseen growth of the single wagonload traffic with the existing infrastructure.

A deeper analysis of the FDFT system benefits will be carried out in the next deliverable of the WP19, benefitting from the outcomes of the demonstration trains that will run as of second half of 2025 and from the results of other focused works.

Appendix 8.5 presents the tests conducted by ADIF and RENFE in Spain to check if the Iberian gauge which is wider than the UIC one has an impact on the FDFT technology. The results of these first tests suggest that there is no impact, meaning that the FDFT equipment for UIC gauge wagons, especially the DAC can also be used in Spain and Portugal.

All figures provided are budgetary estimates without any commitment, intended to give a general indication of the provided costs and benefits of the FDFT system.

3 Abbreviations & Acronyms

Abbreviation / Acronym	Description
ATP	Automatic Train Protection
CBA	Cost-Benefit Analysis
CCU	Consist Control Unit
DAC	Digital Automatic Coupler
DAC CU	Digital Automatic Coupler Control Unit
DPS	Distributed Power System
EDDP	European DAC Delivery Programme
EP Brake	Electro-Pneumatic Brake
ERA	European Union Agency for Railways (European Railway Agency)
ERJU	Europe's Rail Joint Undertaking
FDFT	Full Digital Freight Train
FIFO	First In, First Out
ISO	International Organization for Standardization
LCC	Life Cycle Cost
LCU	Locomotive Control Unit
MCU	Main Control Unit
MY	Marshalling Yards
OBU	On Board Unit
TCMS	Train Control and Monitoring System
TRL	Technology Readiness Level
UIC	Internatioal Union of Railways
WP	Work Package

4 Introduction

4.1 Background

The present document constitutes the Deliverable D19.1, "D19.1: LCC and Benefits Inputs to CBA Phase 1", in the framework of the Flagship Project FP5-TRANS4M-R.

General context of the project

The Digital Automatic Coupling is an innovative technology for rail freight. This technology automates the process of coupling and uncoupling rail vehicles, as well as establishing digital communication links between them. This automation replaces traditional manual coupling, which is laborious, time consuming and presents safety risks.

The main advantage of FDFT system is its ability to optimize operations. It considerably reduces the time needed for the train preparation operations and, to couple and uncouple wagons.

Safety is another key benefit of FDFT system. Manual coupling can be dangerous, involving workers physically moving between wagons. FDFT system eliminates this risk by automating the process, thus reducing the overall probability of accidents in operation.

FDFT system also facilitates data transmission between wagons and energy supply to wagons. This capability enables the automation of train preparation operations (including brake test),real-time monitoring of train status and also the automatic uncoupling. All these functionalities correspond to EDDP DAC basic package.

Figure 1 Representation of a DAC system

The freight part of Europe's Rail JU is called Flagship Project 5, the main ongoing project is called TRANS4RM-R and aims at bringing the DAC technology to a level of maturity allowing first use in commercial operation in 2026 (pioneer trains).

In TRANS4RM-R project Fret SNCF has been entrusted the lead of Work Package 19 that is named “LCC and benefit inputs for CBA”. WP19 started in January 2023 and will last until December 2026.

The Work Package 19 tasks are:

- delivering two successive reports in by the end of the year 2024 and in November 2026 based on costs assessments from suppliers and costs and benefits from TRANS4RM-R demonstrators (Switzerland, Italy, Sweden, Austria, Germany, France)
- supporting EDDP by providing input on costs and benefits for the EDDP CBA work package as described in the Grant Agreement.

4.2 Objective/Aim

4.2.1 Task 19.1 LCC and benefits inputs for CBA described in the Grant Agreement

Task 19.1 scope will cover the following categories of technical enablers: DAC Type 4, DAC Type 5, hybrid coupler for loco, automated brake test, train composition detection (train inauguration), automatic coupling and uncoupling (controlled from a locomotive), train integrity monitoring and safe train length determination,

The current deliverable will include:

- A comparison of e-couplers acquisition and maintenance costs to support decision-making between two proposed e-couplers prototypes.
- Aggregated costs of technical enablers components based on confidential and aggregated input from suppliers
- Aggregated maintenance costs based on confidential and aggregated input from suppliers using LCC EN 60300- 3-3 as foundation: commonly shared maintenance hypothesis and standardization concepts will be the basis for such costs. This will include assumptions on the lifetime of components.
- Installation costs on locomotives and wagons tested in this project including installation time.
- Authorization costs based on time for authorization and administrative costs provided by WP4

4.2.2 Document structure

The document consists of two main sections.

The first section addresses the life cycle cost and is divided into two main subsections:

1. Costs related to the migration phase

- Supply costs: these include the delivery of equipment from the DAC production sites to the workshops responsible for their installation on wagons.
- Installation costs: these correspond to the integration of the FDFT system , including the DAC and the OBU on existing wagons.

2. Costs related to the acquisition and utilisation phase
   - Acquisition costs: these cover the initial purchase of equipment.
   - Maintenance costs: these relate to the inspection and repair of the equipment throughout its lifespan.
   - Disposal benefits: this category includes the advantages of recycling the materials composing the FDFT system.

The second section focuses on capacity benefits in marshalling yards, with an in-depth study based on a concrete case: the Hallsberg marshalling yard in Sweden. The objective is to assess the capacity gains provided by the use of FDFT system in this specific context. However, this analysis does not cover all the other economic benefits that the FDFT system can generate for freight trains. These aspects will be addressed in detail in the second deliverable of WP19.

4.3 Caveats

Before going into the body of the document and presenting the analyses as well as the associated costs and benefits, it is important to remember that these results must be interpreted with caution. They are based on several estimates and assumptions.

This analysis is therefore subject to certain caveats related to implementation and methodological limitations, to the pre-industrialization phase of the FDFT system (which is not yet operational), and to uncertainties associated with the migration plan for this system.

Caveats related to implementation and methodologies

The calculation methods used in the various sections have inherent limitations due to several factors:

- **Data**: The data used in this report comes from sources provided by various stakeholders. Some data may be dated from a few years ago or incomplete, introducing uncertainties into the analyses. Additionally, some information remains confidential due to the current stage of product development.

- **Temporal Scope**: The projections and estimates were made in 2024. Future developments, especially those driven by economic, social or technological factors, could generate significant deviations from the current forecasts.
- **IKOS Arbitrations**: The results presented are based on data provided by various project stakeholders. In cases where conflicting data were received, the subcontractor IKOS had to arbitrate decisions, striving to ensure the greatest possible relevance.

Caveats related to technological maturity (pre-industrialization phase)

This report was prepared while the FDFT system is in the pre-industrialization phase, a stage between design/prototyping and full-scale industrial production. The results should be interpreted in the light of this transitional phase, as variations may occur during industrialization.

- **Design**: The actual design specifications may evolve as new needs or unforeseen constraints emerge, leading to potential adjustments in the design and overall scope. Moreover, certain parts of the FDFTsystem, notably the OBUand the hybrid coupler, may still undergo future changes.
- **Manufacturing**: Uncertainties remain regarding the exact translation of manufacturing processes from a pre-series to full-scale industrial production, particularly concerning efficiency, lead times or supply chain stability.
- **Component Costs**: The estimated component costs in this study rely on current data and market forecasts. These costs may fluctuate due to external factors, such as raw material price changes or supply chain disruptions.
- **Maintenance and operational behaviour**: Projections related to maintenance and operational behaviours are based on assumptions drawn from passenger train experience and freight context.

Caveats related to the migration plan

The assumptions for the migration phase are based on currently available data.

- **Migration planning**: The migration phase is based on assumptions derived from initial migration strategy defined by EDDP. While these assumptions establish an initial framework, they remain subject to changes to accommodate operational and logistical constraints.
- **Number of workshops and production sites**: The exact number of workshops and production sites is not yet fully defined, introducing uncertainty into the projections.
- **UIC installation space acc. to UIC 530**: Cost assumptions have been formulated considering only wagons equipped with the UIC installation space.

5 Life cycle cost (LCC)

This section presents an analysis of the Life Cycle Cost (LCC) applied to the system. It is structured into two parts:

1. FDFT system supply and installation costs.
2. FDFT system utilisation costs, comprising acquisition, maintenance, and disposal costs.

The analysis was conducted based on different parts of the FDFT system. For the wagons, it primarily considers the DAC subsystem (mechanical part) and, in some specific cases, the OBU subsystem which includes also the electrical energy and communication system. For the hybrid coupler applied to locomotives, it includes the hybrid coupler subsystem and the OBU subsystem.

In the section on acquisition costs (§5.2.1), the components of each subsystem are described in detail.

The table below summarizes the subsystems analysed for each part of the document. A cross (X) indicates that the analysis is specific to the corresponding subsystem, while a tilde (~) denotes that the results for locomotive-related subsystems can be considered relatively equivalent to those analysed for wagon-related subsystems.

Table 1 Summary of Subsystems Analyzed for Life Cycle Cost (LCC) Assessment

	Supply & installation costs		FDFT system Utilisation costs		
	Supply	Installation	Acquisition	Maintenance	Disposal
DAC	X	X	X	X	X
Wagon OBU		X	X	X	X
Hybrid coupler	~		X	~	~
Locomotive OBU			?	~	~

5.1 FDFT system Transport and installation costs

In this Life Cycle Cost (LCC) analysis, **transport and installation costs** refer to the expenses associated with the transfer and installation of the FDFT system during the migration phase.

5.1.1 FDFT system supply costs

The FDFT system supply costs have been estimated by IKOS

5.1.1.1 General assumptions on migration costs

To estimate supply costs, three general assumptions regarding migration costs have been defined. The transport costs account for all the DACs to be installed during the migration phase defined by the EDDP (Appendix 8.3). The transport includes the whole coupler system, including the draft gear and the coupler head.

- **Installation workshop hypothesis**: A study conducted by HwH in 2020 estimated that Europe had 694 workshops capable of installing DACs.
  Source of the hypothesis: „Development of a concept for the EU wide migration to a Digital Automatic Coupling System (DAC) for Rail Freight Transportation" Final Presentation on 29 June 2020 in Berlin

- **Production capacity hypothesis:** The production capacity of a factory is estimated at 50,000 DACs per year, based on estimates coming from discussions with manufacturers. With such capacity, approximately four factories would be needed in Europe to meet the anticipated demand for DACs (see appendix 8.3).

- **DAC storage hypothesis:** Storage costs are considered negligible compared to transportation and installation costs, assuming that manufacturing plants implement a FIFO (first-in, first-out) inventory management system, where the oldest inventory items are recorded as sold first. With this management approach, DACs will either be transported directly or stored for a very limited period. Given the estimated number of required manufacturing plants and the network of installation workshops, this hypothesis is consistent.

5.1.1.2 Hypotheses on DAC supply cost

To determine transport costs, a case study was formulated based on the number of DACs to be produced and an estimate of the volume of a DAC transport crate. The case study primarily relies on rail freight transport, supplemented by road freight transport between the production plant and the nearest rail freight station.

- **Hypothesis 1.1:** Based on a flat wagon with a payload of 20 tons per axle and a useful length of 22 meters, it is possible to position 27 DAC crates on the useful surface and stack three rows of DACs per flat wagon, totalling **81 DACs per wagon**.

- **Hypothesis 1.2:** The cost of renting a flat wagon is estimated at **26 € per day**. This cost was estimated with operators.

- **Hypothesis 1.3:** All installation workshops have rail access.

- **Hypothesis 1.4:** To deliver all goods using wagons, the average distance towards installation workshops will be 500 km . The distance of 500 km was estimated using the location of the production workshops of suppliers participating in WP19 and the distance required for all areas of Europe to be covered by at least one of the workshops. **The 500 km is considered as an average distance**.

- **<u>Hypothesis 1.5:</u>** DACs will be transported using single wagons. This hypothesis is justified by the excessively high number of DACs required to form a block train, as well as the need to supply installation workshops as frequently as possible.

- **<u>Hypothesis 1.6:</u>** To deliver all goods using wagons to various installation workshops, it is estimated that the time for installing DACs on the wagon, the transport duration (see Hypothesis 1.4), and the time to unload all DACs from the wagon would be approximately 4 days. This estimation considers the speed of a single wagon and the number of marshalling yards it will need to pass through. This result was validated through discussions with operators.

- **<u>Hypothesis 1.7:</u>** To deliver DACs from manufacturing workshops to a railway station, the haulage will be done using semi-trailers and is estimated to cover a round trip of about 100 kilometres. This hypothesis is based on the following sub-hypotheses:
    - <u>Hypothesis 1.7.1:</u> Based on a semi-trailer with a payload of 24 tons and a volume of 90 m³, it is possible to transport up to **48 DACs per semi-trailer**. This estimation considers the volume of a crate with its DAC, as well as the weight of the crate (including the DAC).
    - <u>Hypothesis 1.7.2:</u> The costs of transport using semi-trailers are estimated at an average of **1,5 € per km** in Europe.
    Source of the hypothesis: https://www.cnr.fr/espace-europe

- **<u>Hypothesis 1.8:</u>** The average transport cost of a single wagon is estimated at **2000€ per trip**. This cost was estimated with operators.

The formula used for calculating the overall supply cost is as follows:

$$Cost_{Global\ haulage} = \left(N_{DAC}/N_{DAC}^{Wagon}\right) \times \left(C_{Wagon} \times T_{Wagon} + C_{Wagon\ delivery}\right) + \left(N_{DAC}^{Wagon}/N_{DAC}^{Truck}\right) \times m_{distance}^{Truck} \times C_{Truck}$$

With:

$$N_{DAC} = Number\ of\ DAC\ to\ be\ produced$$

$$N_{DAC}^{Wagon} = Number\ of\ DAC\ per\ Wagon$$

$$N_{DAC}^{Truck} = Number\ of\ DAC\ per\ Truck$$

$$m_{distance}^{Truck} = Mean\ distance\ travelled\ per\ Truck\ in\ kilometre$$

$$C_{wagon} = \text{Renting}\ cost\ per\ wagon\ per\ day\ for\ a\ delivery$$

$$C_{wagon\ delivery} = Delivery\ cost\ per\ wagon\ for\ a\ delivery$$

$$C_{Truck} = Cost\ per\ kilometre\ of\ a\ Truck$$

$$T_{wagon} = Delivery\ time\ per\ wagon$$

Below is a table summarising the data for the different assumptions required to calculate supply costs.

Table 2 Values used in transport assumptions

Features	Data
Number of DAC to be produce	978718 DAC
Number of DAC transported per Wagon	81 DAC
Number of DAC transported per Truck	48 DAC
Mean distance travelled per Truck in kilometre	100 Km
Renting cost per wagon per day for a delivery	26 €/day
Delivery cost per wagon for a delivery	2000 €
Cost per kilometre of a Truck	1,5 €/km
Delivery time per wagon	4 Day

Based on the hypotheses formulated for this case study and using the formula provided below, **the transportation cost per DAC is estimated at 26 €, or 52 € for fitting 1 wagon (with 2 DAC).** This cost may vary by 5% depending on the fill rate of the semi-trailers.

It is important to note that this cost does not include the cost of all loading and unloading operations of DACs onto the wagons. It is also important to note that the CCU part is not included in this calculation.

5.1.2 FDFT system installation costs

The DAC installation costs have been estimated by IKOS, based on installation times provided by DB and average hourly installation cost provided by ERA.

To estimate the FDFT system installation cost for wagon types, Deutsche Bahn has produced the following report

5.1.2.1 Caveats

Test Environment: All works and tests described herein were conducted in a controlled test environment. Real-world conditions may vary significantly, affecting the reliability and performance of the systems. Readers should be aware that results may not be directly transferable to operational settings.

Occupational safety: This report does not consider possible occupational safety measures. Implementation of the described processes and systems should be accompanied by a thorough safety assessment and adherence to relevant occupational safety regulations and standards.

Team size: All numbers and metrics provided in this report refer to a working team of two people. The efficiency and outcomes may vary with different team sizes and compositions. Adjustments should be made accordingly when applying these findings to different operational contexts.

Retrofitted experiences: The total number of retrofitted experiences is approximately 100 wagons. This sample size may not be representative of the entire fleet or other types of wagons. Users should exercise caution when extrapolating these results to broader applications.

UIC-installation space: The numbers and data available are specifically for wagons with UIC-installation space. Wagons without this installation space may have different performance characteristics and requirements. Users should verify the applicability of these findings to their specific wagon types.

Estimated numbers: The numbers for Basic Package Components are estimated and do not reflect practical experience. These estimates are preliminary and should be validated through actual implementation and testing. Users are advised to conduct their own assessments to confirm the accuracy of these estimates.

This study provides an installation time for two types of wagons:

- Wagon with UIC-installation space, Type: vertical support, Axles 2
- Wagon with UIC-installation space, Type: vertical support, Axles 4

5.1.2.2 Coupler components working time installation

The objective of this first part is to explain coupler components working time installation by dividing the installation into several partials' steps of installation. The results of the study conducted by Deutsche Bahn are presented below.

Table 3 Installation time for coupler part

Wagon Type	Components	Components	Total Time per wagon in min.
Wagon with UIC-installation space, Type: vertical support, Axles 2	Draft gear-DAC ready, installation - over 20 partial steps	Coupler head and coupling shank, installation coupler front part - over 15 partial steps	
time in min. per unit	143 min, with 2 persons	64 min with 2 persons	
Time in min. per Wagon	287 min work)	129 min work)	416 min. working time with 2 persons
Wagon with UIC-installation space, Type: vertical support, Axles 4	- over 30 partial steps	- over 15 partial steps	
time in min. per unit	164 with 2 Persons	64 with 2 persons	
Time in min. per wagon	327	129	456 min. working time with 2 persons

The analysis indicates that the installation of a Digital Automatic Coupler on a wagon with UIC-installation space, featuring a vertical support and 2 axles, **requires 416 minutes with 2 persons, i.e. a total of 832 min of technician time**. Similarly, the installation of a DAC on a wagon with UIC-installation space, featuring a vertical support and 4 axles, **requires 456 minutes with 2 persons, i.e. a total of 912 min of technician time**. The overall installation time includes uninstalling buffers and screw couplers.

5.1.2.3 DAC basic package components working time installation

The objective of this part is to explain Basic Package components working time installation by dividing the basic package into components.

Table 4 Installation time for CCU part

Components	Installation time in min.
Power System / data communication / installation of wiring	120 min.
Hardware boxes (WOBU, energy management)	20 min.
Sensor technology (train integrity, wagon order)	20 min.
Automated Brake Test	240 min
Total Time per wagon	400 min.

The analysis shows that the installation of basic package equipment should take **approximately 400 min per wagon by two persons as a team, i.e. approximately 800 min of technician time per wagon**.

5.1.2.4 DAC components and basic package components working time installation

Table 5 Global working time installation

Wagon type	Installation time in min. for 2 persons
Wagon with UIC-installation space, Type: vertical support, Axles 2	816
Wagon with UIC-installation space, Type: vertical support, Axles 4	856

The table provides the installation times for a Digital Automatic Coupler (DAC) on different types of wagons, each with UIC-installation space and vertical support, but with varying numbers of axles. Specifically, for a wagon with 2 axles, the installation requires **816 minutes of working time for a team of two people, i.e. 1632 min of technician time**. For a wagon with 4 axles, the installation time increases to **856 minutes for the same team size of two people, i.e. 1712 min of technician time**.

To switch from installation times to installation costs and to ensure the confidentiality of the collected data (hourly cost of workshop technician), a "EU survey" has been made with the support of ERA. This survey has been sent to workshop companies and wagon keepers from all over Europe. ERA received 22 answers allowing the calculation of an average technician hourly cost for wagon and for locomotive workshops. To weight this average cost, ERA assumed that wagons and locomotives are retrofitted in the countries in which they are registered, and that the values provided for countries are representative for broader regions. This led to the following European weighted hourly workshop costs for fitting DAC: **74 € per hour for wagons and 79 € per hour for locomotives**.

Knowing the workshop cost and the installation time, the estimation of the **installation costs for wagons are:**

Table 6 Installation costs

	Wagon with UIC-installation space, Type: vertical support, Axles 2	Wagon with UIC-installation space, Type: vertical support, Axles 4
Draft gear installation cost	707 €	806€
Coupler Head installation cost	318 €	318 €
Basic package components installation cost	987 €	987 €
Total Cost	2012 €	2111 €

Due to a lack of data and experience, the installation cost of hybrid couplers on locomotives is not included.

5.2 FDFT system acquisition and utilisation costs

5.2.1 Acquisition costs

The acquisition costs have been estimated by IKOS

The acquisition costs were sourced from industrial partners through the subcontractor IKOS. The data collection involved four DAC manufacturers (Dellner, Knorr-Bremse, Voith, and Wabtec) and two locomotive manufacturers (Alstom and Siemens).

5.2.1.1 Scope of analysis

To calculate acquisition costs, a predefined list of components was established. The analysis focuses on the "basic package," which includes the following DAC functionalities:

- Train composition detection, including safe train length determination
- Train integrity monitoring
- Automated brake testing
- Decoupling of consists from a locomotive and via local push buttons

The DAC system was broken down into subsystems for analysis. For wagons, two subsystems were defined: the **Coupler Subsystem** and the **CCU Subsystem**. The table below details the components of these subsystems:

Table 7 DAC "basic package" components for the wagon

Subsystems	Components
Coupler part	Coupler's head and shank
	Draft gear
	Vertical support
	Brake Pipe Valve
	E-coupler and actuator
	Junction box
	DACCU
CCU part	Control Unit
	Push button for local decoupling
	Power Supply System

	Communication system based on Single Pair Ethernet
	Sensors for brake pipe monitoring and automated brake test

For locomotives, two additional subsystems were defined: the **hybrid coupler subsystem** and the **LCU/MCU subsystem**. Their components are listed below:

Table 8 DAC "basic package" components for the locomotive

Subsystems	Components
Hybrid coupler part	Hybrid coupler's head and shank
	Draft gear
	Vertical support
	E-coupler and actuator
	Junction box
OBU part	Control Unit
	Push button for local decoupling
	Communication system based on Single Pair Ethernet
	Sensors for brake pipe monitoring and automated brake test
	~~Traction Unit Power Supply System~~ è *not included*
	~~CCU – ATP I/F~~ è *not included*
	~~CCU – TCMS I/F~~ è *not included*

Due to anti-trust concerns, only components developed by at least three manufacturers were included. Therefore, the power supply system and interfaces with ATP and TCMS were excluded, as they are only developed by the two locomotive manufacturers.

Moreover, the costs associated with engineering (adaptation of the draft gear of the locomotive according to each different type of locomotive, potential weight change to be able to fit the hybrid coupler without exceeding 22,5 tons / wheelset and certification are not included in the values.

5.2.1.2 Data collection and calculation method

The following information was collected from the manufacturers through IKOS:

- **A market price per unit of a single coupler part of the DAC "basic package"** (for a **series of 1,000 units**; each wagon requires two coupler parts).
- **A market price per unit of a single CCU part of the DAC "basic package"** (for a **series of 1,000 units**; each wagon requires one CCU).
- **A market price per unit of a single hybrid coupler part of the hybrid DAC "basic package"** (for a **series of 100 units**; each locomotive requires two hybrid coupler parts).
- **A market price per unit of a single LCU/MCU part of the Hybrid DAC "basic package"** (for a **series of 100 units**; each locomotive requires one LCU/MCU).

The manufacturers may provide all or only some of these four prices. To ensure compliance with anti-trust regulations, the aggregated market prices for each of the four sub-systems will only be displayed if at least three responses are received per sub-system.

Once the data was collected, the final cost calculation method incorporated economies of scale. The table below illustrates the calculations performed based on the information provided by the manufacturers. Some manufacturers provided a price range. In such cases, the average of the two boundary values was calculated to determine a single cost.

Table 9 Calculation method for acquisition costs

	Manufacturer a	[...]	Manufacturer n	Average Acquisition Cost	Av. Acquisition Cost with Scaling Factor
Coupler part market price	a_{ccu}	[...]	n_{ccu}	m_{ccu}	M_{ccu}
CCU part market price	a_{meca}	[...]	n_{meca}	m_{meca}	M_{meca}

Information communicated to IKOS by the manufacturers | Information processed internally by IKOS | Information communicated in the deliverable 19.1

To account for economies of scale, a formula based on experience curves was applied. The experience curve operates on the premise that the more frequently an activity is performed, the easier and more efficient it becomes. Empirical research has demonstrated that as the cumulative number of units of a product increases, the cost of producing each unit decreases at a predictable rate. Each time production doubles, the unit production cost reduces by a fixed percentage (see graph below).

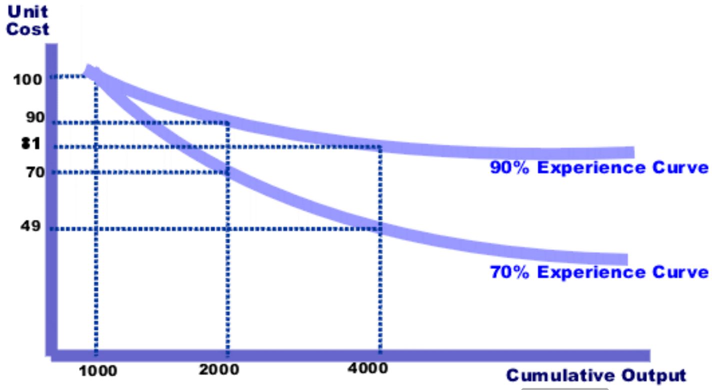


Figure 2 Experience curve

The formula used is:

$$P(N) = P(\text{initial}) \times R^{log_2(N)}$$

With:

- $P(N)$: The unit value for a series of N*1000 products (for wagon subsystems) or N*100 products (for locomotive subsystems).
- N: Depends on the number of products and the number of manufacturing lines. Based on the migration plan (see Appendix 8.3), **an annual production assumption per manufacturing line was made: 50 000 DACs for wagons** (50 000 coupler parts and 25 000 CCU parts) **and 1 500 Hybrid DACs for locomotives** (1 500 hybrid coupler parts and 750 LCU/MCU parts).
- $P(\text{initial})$: The unit value for a single product for a series of 100 or 1000 products
- R : The experience ratio. For this type of product (DAC), **the experience ratio is estimated to be approximately 95% for the coupler parts and 92% for the electronic parts**. These assumptions have been integrated into the calculations.

5.2.1.3 Results and remarks

After applying the calculation method that accounts for economies of scale, the results are as follows:

Table 10 Acquisition costs

Wagon -Subsystems	Average Acquisition Cost with Scaling Factor			Consistency estimation
	for 1 000 wagons/year per factory	for 5 000 wagons/year per factory	for 25 000 wagons/year per factory	
DAC part	13 976 € / DAC	12 407 € / DAC	11 014 € / DAC	Strong
OBU part	11 878 € / OBU	9 787 € / OBU	8 064 € / OBU	Limited
Total for 1 wagon	39 829 €	34 600 €	30 091 €	
Locomotive - Subsystems	**Average Acquisition Cost with Scaling Factor**			**Consistency estimation**
	for 100 locomotives /year per factory	for 250 locomotives /year per factory	for 750 locomotives /year per factory	
Hybrid coupler part	35 788 € / coupler	33 442 € / coupler	30 831 € / coupler	Moderate
OBU part *(power supply system and interfaces with ATP and TCMS not included)*	12 467 € / OBU	11 166 € / OBU	9 783 € / OBU	Weak

Total for 1 locomotive	84 043 €	78 049 €	71 445 €	

It is important to consider the following remarks for a better understanding of the values presented in the preceding table.

Remarks related to the coupler part of the DAC for wagons:

- A strong consistency is observed in the costs proposed by the various manufacturers for the coupler part of the DAC for wagons. This indicates uniformity in the design across different suppliers and similarity in the manufacturing process estimates, suggesting that these estimations are likely reliable and consistent.

Remarks related to the CCU part of the DAC for wagons:

- A relatively low consistency is observed in the costs proposed by the various manufacturers for the CCU part of the DAC for wagons. This highlights a significantly lower level of maturity in the development of this component. This observation aligns with the currently very limited presence of fully functional DAC 5 units in test fields.

Remarks related to the hybrid coupler part of the DAC for locomotive:

- A moderate consistency is observed in the costs proposed by the various manufacturers.
- Determining the cost of a locomotive coupler is challenging due to significant uncertainties related to the locomotive design, required adaptations, and special solutions.
- Engineering efforts can vary significantly depending on the locomotive, with some requiring substantial adaptations. This can lead to much higher costs.
- Material costs differ across platforms, particularly due to varying crash worthiness requirements, ranging from no constraints to complete crash management systems with deformation tubes and decoupling systems. This contributes to significant price variability.

Remarks related to the LCU/MCU part of the DAC for locomotive:

- A very low consistency is observed in the costs proposed by different manufacturers for the LCU/MCU component of the DAC for locomotives. This highlights a low level of maturity in the development of this component. This observation is further supported by the fact that the specifications of the LCU/MCU component can vary depending on whether it is for a retrofitted locomotive or a new one. **Therefore, the costs associated with this component should be interpreted with great caution.**

General remarks

- The assumptions regarding the number of DACs include all wagons and locomotives in Europe. The difference in track geometry on the Iberian Peninsula does not affect the design of the DACs (see Appendix 8.5).

5.2.2 Maintenance costs

The maintenance costs have been estimated by IKOS

The DAC is currently in the development phase, so it is essential to specify that all data relating to maintenance operations and costs are based on estimates. Although the values presented offer an order of magnitude and are partially representative, they should not be considered definitive for the maintenance of the DAC. **Additionally, the costs related to wagon downtime and transport to maintenance workshops are not accounted for, as the proposed DAC maintenance phases can be integrated into the maintenance schedules of other wagon components** (brakes, rolling components, etc.). **The training costs for maintenance technicians are not included in the cost analysis.**

5.2.2.1 Maintenance hypothesis

For the maintenance cost hypotheses, a detailed list of maintenance operations to be considered has been developed. To ensure the most realistic hypotheses, the various maintenance procedures are based on an analysis of:

- Maintenance interventions on automatic couplers for passenger trains.
- Maintenance interventions on current freight wagons (without DAC).
- Maintenance section of the cost evaluation for the electrical part of the DAC (E-coupler).

Maintenance procedures have been adjusted to consider the particularities of freight trains. Consultations with operators and suppliers have ensured a comprehensive and relevant approach, effectively addressing the particularities of freight. The approach to defining maintenance operations based on current passenger and freight operations has been validated by the manufacturers.

The maintenance interventions for the freight DAC have been divided into four phases:

- Operational Check-up: Occurs annually.
- Examinations, Tests and Inspections: Occur every three years.

- Minor Overhaul: Occurs every six years.
- Main Overhaul: Occurs every twelve years.

The division of maintenance interventions into four phases, along with their periodicity (1 year, 3 years, 6 years, and 12 years), has been reviewed by industry stakeholders and deemed acceptable.

Table 11 Operational check-up

List of operations	Intervention components	Details
Cleaning and degreasing	Coupler Head; Electrical Coupler	Cleaning and degreasing of the coupling head and electrical coupler to ensure optimal connectivity and prevent any accumulation of dirt on functional areas.
Lubrication - Greasing	Coupler Head; Electrical Coupler	Lubrication and greasing of the components of the coupler head and electrical coupler to reduce friction and prevent premature wear.
Visual inspection	Global; Manual Uncoupling Command	Visual inspection of the entire coupler and all the commands to detect any visible damage or signs of degradation.
Operational tests and inspection	Sealing (Pneumatic System)	Operational test and inspection of the sealing of the pneumatic system to ensure that there are no leaks and that the pneumatic components are working properly.

Table 12 Examinations, tests and inspections

List of operations	Intervention components	Details
E-coupler inspection	Mechanical Part; Cover Position; Electrical part	Inspection of the mechanical part, the cover position, and the electrical section of the e-coupler to verify their condition and alignment.
Pneumatic system inspection	BP Valve, Seals, Tubes	Verification of the BP valve, seals, and hoses of the pneumatic system to ensure their integrity and prevent leaks.

Mechanical system inspection	Coupling and Uncoupling Device	Inspection of the coupling and uncoupling device to ensure proper mechanical functionality.
Coupler head components inspection	Front Plate; Centring Cone; Horn	Examination of the front plate, centring cone, and horn to verify the alignment and functionality of the guidance components.
Draft Gear inspection	Draft gear Device (Deformation Indicators)	Inspection of the draft gear device to detect any wear or structural deformation by using deformation indicators.
CCU inspection	Software Update; Calibration	Inspection of the Consist Control Unit (CCU) to perform a software update and calibration of the systems, ensuring operational accuracy.

Table 13 Small overhaul

List of operations	Intervention components	Details
Small overhaul coupler	Sealing; mechanical spare parts; data/power contact	Replacement of sealing gaskets, mechanical spare parts, and data/power contacts in the coupler to ensure the reliability of the connection.
Small overhaul CCU	Battery	Replacement of the battery in the Consist Control Unit (CCU) to maintain stable and efficient power supply.

Table 14 Main overhaul

List of operations	Intervention components	Details
Main overhaul - coupler	All	Complete overhaul of the coupler part, including a thorough inspection and replacement of worn components to extend the coupler's lifespan.

Main overhaul - CCU	All	Complete overhaul of the Consist Control Unit (CCU), including a detailed inspection and potential replacement of essential components.

In the maintenance cost hypotheses, three types of maintenance are defined:

- **Systematic preventive maintenance:**

The goal of preventive maintenance is to reduce malfunctions by ensuring regular upkeep of equipment, systematic inspection of components, and addressing minor issues before they become critical. This approach is crucial for couplers, as it aims to anticipate failures and preserve equipment performance, thereby avoiding any damaging malfunctions.

The implementation of preventive maintenance is based on a maintenance plan established according to several criteria, such as the age of the equipment, the level of wear, or the number of kilometres travelled. This plan is defined before the coupler is put into operation.

Among the various forms of preventive maintenance, systematic maintenance stands out for its regularity. It is carried out at predefined intervals and involves systematically replacing certain parts and components, regardless of their state of wear or deterioration. This type of intervention is particularly recommended for critical elements, where a small failure could have significant operational consequences, such as sealing joints, small mechanical parts, or batteries.

In our assumptions, systematic maintenance interventions are considered only during the minor overhaul phase, scheduled every 6 years, and the main overhaul, carried out every 12 years.

- **Conditional preventive maintenance:**

Conditional preventive maintenance is a specific form of preventive maintenance that relies on monitoring operational parameters, performance indicators, and the wear of equipment. This approach enables technicians or maintenance managers to identify the need for corrective interventions to anticipate failures or malfunctions.

Unlike systematic maintenance, the conditional maintenance plan does not set a fixed schedule for component replacement. Instead, it focuses on inspection and verification actions to assess the condition of components. This method adapts to the actual usage conditions of the equipment, which can directly influence the level of component degradation (e.g., operational or environmental conditions).

In our assumptions, conditional maintenance interventions are limited to maintenance operations involving inspection or monitoring of components, as well as to the main overhaul phase.

- **Corrective maintenance:**

Corrective maintenance is not based on a pre-established plan or schedule but is initiated when a component presents a fault or malfunction. The associated interventions involve repairing or replacing the defective component. The primary goal of corrective maintenance is to resolve a malfunction, anomaly, or non-conformity to restore the equipment's proper operation.

In our assumptions, corrective maintenance interventions are not linked to the four maintenance intervention phases. Therefore, an annual cost estimate for corrective maintenance, specific to the DAC, will be conducted.

5.2.2.2 Maintenance cost hypothesis

Maintenance cost hypothesis for the coupler part

The table below presents the cost estimates associated with each of the four maintenance phases for the coupler part (mechanical part) of the DAC.

Table 15 Maintenance costs for the coupler part

Maintenance Interventions	List of Operations	Duration (min)	Human Resource Cost (€)	Systematic Maintenance Cost (€)	Conditional Maintenance Cost (€)	Corrective Maintenance Cost (€)
Operational check-up (every 1 year)	**Cleaning and degreasing**	5	35		4	30 / y
	Lubrication - Greasing	5				
	Visual inspection	3				
	Operational tests and inspection	15				

Examinations, tests and inspections (every 3 years)	**E-coupler inspection**	3	120		40	
	Pneumatic system inspection	60				
	Mechanical system inspection	15				
	Coupler head components inspection	15				
	Draft Gear inspection	5				
Small overhaul (every 6 years)	**Small overhaul coupler**	30	37	400		
Main overhaul (every 12 years)	**Main overhaul coupler**	360	444	1450	650	

Duration

The intervention durations for each operation have been established based on the intervention times for automatic couplers for passenger trains, adjusted to account for the specifics of freight operations. These durations were also validated through discussions with manufacturers.

Human resource costs

For the calculation of human resource costs, the hourly cost of a technician working on a wagon is estimated at **74 €**, according to a study conducted by the European Railway Agency (ERA). This cost has been applied proportionally to the duration of each maintenance operation.

Maintenance costs

- Systematic maintenance costs: The cost of systematic maintenance, carried out during the minor overhaul phase, is estimated at **400 €**. This estimation includes the overall estimated cost of parts systematically replaced every 6 years, such as sealing gaskets, certain small mechanical parts, and data/power contacts.

- Conditional maintenance costs: Conditional maintenance costs, related to the operational check-up phase as well as examinations, tests, and inspections, are calculated based on the probability of failure requiring an intervention equivalent to a minor overhaul:
    - Operational check-cp (annual): An assumption of **1 out of 100 DACs** requiring maintenance has been made. This corresponds to **1% of 400 €**, resulting in a conditional maintenance cost of **4 €**.
    - Examinations, tests, and inspections (every 3 years): An assumption of **1 out of 10 DACs** requiring maintenance has been made. This corresponds to **10% of 400 €**, resulting in a conditional maintenance cost of **40 €**.

- Main overhaul maintenance costs: The costs associated with the major overhaul have been estimated as a percentage of the acquisition cost. These costs have then been allocated between the systematic maintenance and the conditional maintenance. The detailed estimates are summarized in the table below, based on an analysis of passenger train couplers and discussions with project stakeholders.

Table 16 Main overhaul maintenance costs

	Percentage of maintenance cost relative to acquisition cost	Percentage of systematic maintenance in maintenance cost	Percentage of conditional maintenance in maintenance cost
Coupler head & shank	10%	40%	60%
Draft gear	20%	90%	10%

Pneumatic system	10%	50%	50%
E-coupler & actuator	20%	90%	10%

- Given that the DAC is currently in the development phase, estimating corrective maintenance costs is challenging. Therefore, a provisional assumption of **30 € per year per DAC** has been adopted. This assumption is based on discussions with manufacturers. This provisional estimate allows for initial budgeting and planning, with the understanding that more accurate data will be available as the DAC progresses through its development and operational phases.

Table 17 Summary table for coupler maintenance

Operational Check-Up	Examinations, Tests, and Inspections	Small Overhaul	Main Overhaul	Corrective Maintenance	Cumulative maintenance cost of coupler part	Net present maintenance cost of coupler part
Every Year	**Every 3 Years**	**Every 6 Years**	**Every 12 Years**	**Averaged over 1 year**	**Lifespan: 30 years**	**Lifespan: 30 years**
39 €	**160 €**	**437 €**	**2544 €**	**30 €**	**10 943 €**	**6 727 €**

The cumulative cost, for one year for the coupler part per DAC, breaks down as follows: **224 €/year** for spare parts, **110 €/year** for human resources, and **30 €/year** for corrective maintenance.

The net present cost of maintenance is used to determine the cost of maintaining the coupler part of the DAC, factoring inflation into the calculation. The formula is as follows:

$$C = \sum_{t=1}^{n} \frac{c_t}{(1+r)^t}$$

With : n is the number of years in the life cycle, in this case 30 years

c_t is the maintenance cost for year t (see appendix 8.4)

r is a rate indexed to inflation, 3% based on ECB data

Maintenance cost hypothesis for the CCU part

The table below presents the cost estimates associated with each phase of maintenance for the Consist Control Unit (CCU) part of the DAC. **It is important to note that the values used for CCU maintenance are based on much less robust assumptions compared to the coupler part. Therefore, the values presented should be interpreted with considerable caution.**

Table 18 Maintenance costs for the CCU part

Maintenance Interventions	List of Operations	Duration (min)	Human Resource Cost (€)	Systematic Maintenance Cost (€)	Conditional Maintenance Cost (€)	Corrective Maintenance Cost (€)
Examinations, tests and inspections (every 3 years)	**CCU inspection**	15	19			30 / y
Small overhaul (every 6 years)	**Small overhaul CCU**	10	12	1000		
Main overhaul (every 12 years)	**Main overhaul CCU**	180	222	1500		

Duration

The intervention durations for each operation have been established based on discussions with manufacturers. These durations reflect the time required to perform various maintenance tasks effectively.

Human resource costs

For the calculation of human resource costs, the hourly cost of a technician working on a wagon is estimated at **74 €**, according to a study conducted by the European Railway

Agency (ERA). This cost has been applied proportionally to the duration of each maintenance operation.

Maintenance costs

- Systematic maintenance costs: The cost of systematic maintenance, carried out during the minor overhaul phase, is estimated at **1000 €**. This estimation includes the replacement of the CCU battery every 6 years.
- Conditional maintenance costs: For the CCU part, there are no conditional maintenance costs as it consists of electronic equipment.
- Main overhaul maintenance costs: The cost of systematic maintenance, carried out during the minor overhaul phase, is estimated at **1500 €**. This estimation includes the replacement of the controller and all essential electronic components critical to the proper functioning of the CCU, every 12 years.
- Given that the DAC is currently in the development phase, estimating corrective maintenance costs is challenging. Therefore, a provisional assumption of **30 € per year per DAC** has been adopted.

Table 19 Summary table for CCU part maintenance

Examinations, Tests, and Inspections	Small Overhaul	Main Overhaul	Corrective Maintenance	Cumulative maintenance cost of CCU part	Net present maintenance cost of CCU part
Every 3 Years	Every 6 Years	Every 12 Years	Averaged over 1 year	Lifespan: 30 years	Lifespan: 30 years
19 €	1012 €	1720 €	30 €	9 590 €	5 827 €

The cumulative cost, for one year for the CCU part per DAC, breaks down as follows: **266 €/year** for spare parts, **23 €/year** for human resources, and **30 €/year** for corrective maintenance.

The net present cost of maintenance is used to determine the cost of maintaining the CCU part of the DAC, factoring inflation into the calculation.

5.2.3 Disposal benefits

The disposal benefits have been estimated by IKOS

The end-of-life benefits in this Life Cycle Cost analysis are based on the ISO 21106:2019 standard and the current values of material buyback via scrap dealers.

The ISO standard provides a method for calculating the recyclability and recoverability rates of rolling stock. The defined method applies to the design of new rolling stock. The calculation method is applicable to all stages of the rolling stock's life cycle. The recyclability and valorisation rates are calculated based on the product design plan. Future recycling technologies or predicted trends in the recycling industry are excluded from consideration in this calculation method.

The ISO standard takes into account four main processing methods: reuse, recycling, energy recovery, and disposal. Process losses of recycling are treated in the disposal stage.

The calculation of recyclability and recoverability rates is carried out through the following three steps, for which all materials, components, or both must be considered at each step:

1. Pre-treatment step:
2. Dismantling step:
3. Shredding step.

These three steps are actually applicable to the end-of-life processing, for which all materials, components, or both can be reused, recycled, or valorised at each step. Based on the understanding of these steps, the preliminary design for disassembly and recyclability should be considered in the design and development of rolling stock to improve its recyclability and recoverability.

Table 20 : The main end-of-life treatment processes

Pre-treatment	Extraction of fluids: Send to recycling, energy recovery, or disposal. Depollution: Removal of hazardous components.
Dismantling	Disassembly of parts for reuse or to facilitate the separation of materials for recycling or disposal. Manual separation of materials as much as possible. Metals: Send to recycling. Polymers: Send to recycling or energy recovery.
Shredding	Remaining part of the vehicle: Send to shredding. Recycling of metals.
Residues	Non-metallic residues from shredding: Preferably recycled before being sent to incineration.

Through the application of the method and adherence to the flowchart (see figure below), the end-of-life benefits of the DAC due to its recycling have been estimated.

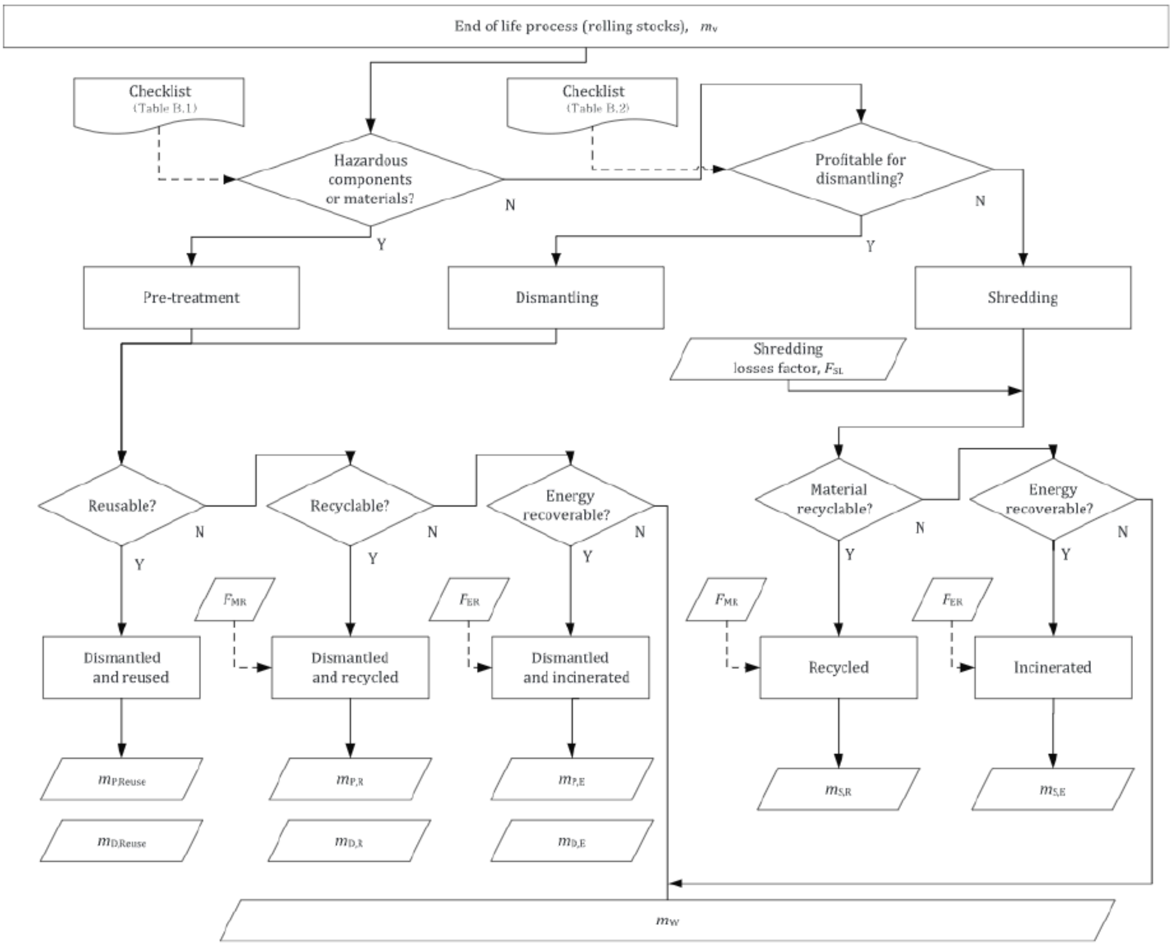


Figure 3 Three stages of the end-of-life treatment for rolling stock

The estimation was constructed by considering various information and remarks collected during interviews with different companies. Additionally, for reasons of confidentiality and clarity, the distribution of masses was simplified for the calculation.

By distributing the masses of different types of materials according to the four main processing methods—reuse, recycling, energy recovery, and disposal (see ISO21106:2019 annexe A)—and taking into account the buyback prices of recyclable raw materials (https://www.sorevo.com/fr/tarifs), it was calculated that at the end of its life, the DAC could represent **a benefit of more than 300 € (not including the resale of the battery)**.

6 Capacity Benefits in Marshalling Yards

The Capacity benefits in Marshalling yards have been estimated by the Swedish university KTH

The comprehensive KTH study, which includes detailed information on marshalling yards—specifically the Hallsberg Marshalling Yard in Sweden—along with operations at Hallsberg and an overview of the AnyLogic model, is available in Appendix 8.2.

6.1 Assumptions and scenarios

6.1.1 Model build with AnyLogic to assess capacity in marshalling yard

To create the AnyLogic simulation model, certain data was collected, and assumptions were made, as you can see in the following subsections. The model developed is an AnyLogic model designed to assess the positive impact of DAC on the capacity of the Hallsberg marshalling yard. The model consists of two components presented in sub sections.

6.1.2 Layout of the Hallsberg marshalling yard

The first component of the AnyLogic model is the layout of the marshalling yard, shown in Figure 4, which is divided into three sections representing the arrival yard, the classification yard and the departure yard. The layout is only used to illustrate the number of tracks and their respective lengths, without having any direct influence on the behaviour of the trains.

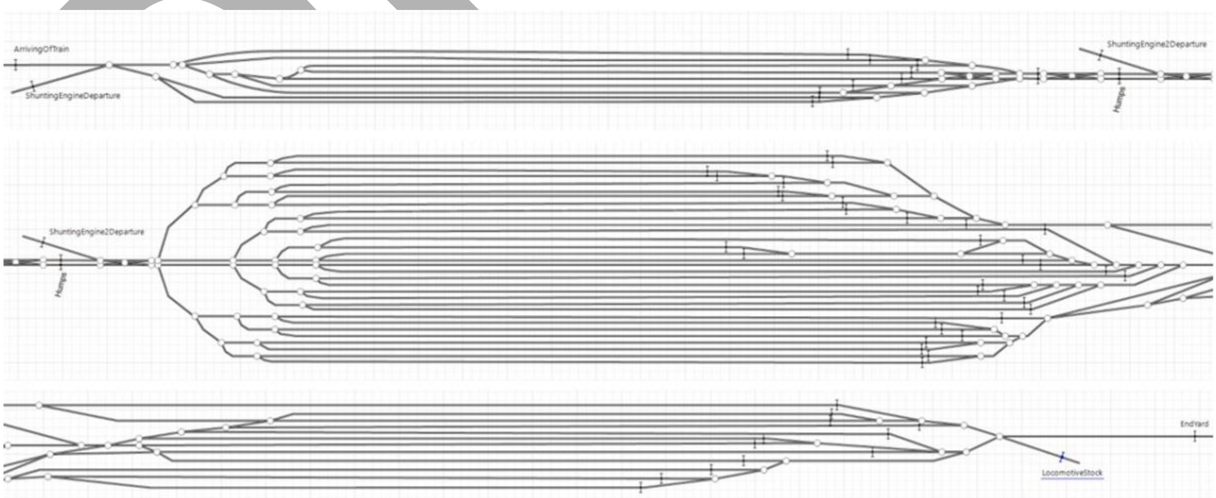


Figure 4 Hallsberg's marshalling yard layout

The data for the marshalling yard itself, including the number of tracks in the arrival, classification and departure yards and the length of each track, was taken directly from (NJDBwebb, n.d.) one of the pages of Trafikverket, the Swedish Transport Administration. Hallsberg marshalling yard is a marshalling yard consisting of three major sub-yards: an arrival yard, a classification yard and a departure yard. The marshalling yard consists of a total of 8 tracks in the arrival yard with varying lengths of 590 to 690 m, which are connected to the classification yard via a double hump and 32 tracks in the classification yard with varying lengths of 374 to 760 m. Finally, the departure yard consists of 12 tracks with lengths of 562 to 886 m.

The marshalling yard consists of a double hump between the arrival and the classification yard. All trains must cross one of these two humps, where their destination is determined. For safety reasons, however, the two humps cannot be used at the same time.

6.1.3 Blocks of Hallsberg marshalling yard

The second part of the AnyLogic model consists of blocks that represent the various movements and tasks in the marshalling yard. The blocks are shown in Figure 21 (Appendix 8.2)**Error! Reference source not found.**, and again the blocks representing the various actions in the three different yards are split up.

In contrast to the layout, the blocks are responsible for the movement of the wagons or wagon sets. The yellow circles represent the creation (Source) and termination (Dispose) of the train. The meaning of the symbols in **Error! Reference source not found.** is summarized in **Error! Reference source not found.**. Trains are created at the beginning of the model and at three other times throughout the model. The first time for the creation of the shunting locomotive, which is responsible for the movement within the arrival yard, the second time for the creation of the second shunting locomotive, which is responsible for the movement within the classification yard, and the third time for the creation of the locomotive that will pull the wagon set at the end. The completion of the model is used on two occasions. The first time the first locomotive is disposed of at the end of the yard, while the second time the complete train is disposed of as soon as it has left the yard. The yellow rectangles are used to facilitate the movement of wagon sets from one location to another. Each movement, as described in Table 22, Table 23, Table 24**Error! Reference source not found.** is represented by this type of block in the model, with the specified speeds incorporated into the block. Yellow triangles are employed to couple and decouple the trains, and they are utilised in the model in accordance with the specifications outlined in Table 22, Table 23, Table 24.

The operations described in the same tables (including coupling and decoupling, as the action of coupling and decoupling is immediate in AnyLogic) are represented in the model by delay blocks (dark blue rectangle). The light blue rectangles are used to allocate or release a resource in the model. They are used to avoid potential conflicts at certain points, such as the hump, where only one resource is available so that only one wagon set can use the hump at any given time. Alternatively, there are two rectangles for the use of one of the two shunting locomotives. In this case, too, only one shunting locomotive is available, which implies that two waiting trains are dispatched one after the other. The rule implemented is FIFO (First In First Out), which means that the first train to request a shunting locomotive is also the first to have access to it. Another block that is used twice in the model is the hold block (red circle), which represents the need for a train, and in this case a shunting locomotive, to wait before leaving its position. In this case, a shunting locomotive may only leave its position if a train needs to be pulled. Finally, the last block is the blue diamond, which represents the selection of an exit based on a specific condition. This block was used twice in the model. Initially, it is used in the arrival yard to determine whether the wagon in question is a standard wagon, which means that the decoupling process should continue. If the wagon is a shunting locomotive, the decoupling process is considered complete. The second block is used in the classification yard. When a new wagon arrives, the system checks whether there are enough wagons for the train to continue to the next stage or whether it has to wait for more wagons to arrive.

Table 21 Meaning of symbols in AnyLogic model

Yellow circle	the creation (Source) and termination (Dispose) of the train
Yellow rectangle	facilitates the movement of wagon sets from one location to another
Yellow triangle	couples and decouples the wagon sets
Dark blue rectangle	delays blocks
Light blue rectangle	allocates or releases a resource in the model.
Red circle	represents the need for a wagon set
Blue diamond	represents the selection of an exit

The output of this model is a simulation of the movement of trains, locomotives, and shunting locomotives. The figure below (Figure 22 – Appendix 8.2**Error! Reference source not found.**) shows the layout of the Hallsberg's marshalling yard, where a number of trains can be seen.

The original data for the duration of each action for the trains within each marshalling yard comes from the Hallsberg marshalling yard and is shown in Table 22, Table 23, Table 24 respectively. Table 22 lists the tasks involved in the arrival of the train at the arrival yard, the necessary manual coupling and decoupling and their duration in the first column.

Table 22 Dedicated time in minutes to different required tasks with DAC level 4 and level 5 after train arriving

Tasks	Time (min)		
	Conventional	DAC 4	DAC 5
Reserve time (based on braking before the signal)	0.23	0.23	0.23
Driving	2.63	2.63	2.63
Securing wagons and decoupling them from locomotive	2.3	1.8	1.7
Checking and preparation	0,5 min per wagon	0,5 min per wagon	0
Coupling to the shunting locomotive	0.8	0.05	0.03
Towing, releasing brakes, waiting for signals	1	1	1
Pushing wagons over to the hump	230 + 40 m with 1.2 m/s		
Rolling over hump	7.75	7.75	7.75

A tabular summary of the tasks to be performed in the classification yard, the manual coupling and decoupling activities and the duration of all activities can be found in the second column of Table 23

Table 23 Dedicated time in minutes to different detailed operational task with DAC level 4 and level 5

Tasks	Time (min)		
	Conventional	DAC 4	DAC 5
Coupling wagons and brakes	80 m/min + 45 s/wagon	0	0
Time for filling the brake system with air	15	15	15
Testing the brake system	1	1	1

Refilling the brake systems after the test	0.33	0.33	0.33
Brake test, hitting the brakes, controlling each wagon	15	2	2
Releasing brakes	2	2	2
Controlling that all brakes have been released	15	1.5	1.5
Release buffer stops	0.25	0.25	0.25
Activate brakes	0.08	0.08	0.08
Time for driving the locomotive to the wagons and coupling it	0.17	0.1	0.1
Releasing brakes	2	2	2
Simple brake test	1	1	1
Time for departure including path reservation	2.5	2.5	2.5
Time for activating buffer stops, relays, reaction time	1	1	1

A tabular overview of the activities in the departure yard, manual coupling and decoupling and the duration of all activities in the order in which they occur can be found in Table 24.

Table 24 Dedicated time in minutes to different required tasks with DAC level 4 and level 5 before the train departures

Tasks	**Time (min)**		
	Conventional	DAC 4	DAC 5
Driving	1.6	1.6	1.6
Decoupling from the shunting locomotive	1	0.8	0.5
Driving the shunting locomotive away	0.2	0.2	0.2
Driving the line locomotive to wagons	0.2	0.2	0.2
Coupling to the line locomotive	0.17	0.1	0.1
Charging the brake pressure	5	5	5
Simple brake tests	1	1	1

Waiting for the signal	2	2	2
Departing	2	2	2

When creating the AnyLogic model, the speed of the train arriving at the marshalling yard and the speed of the shunting and line locomotives within the marshalling yard was also required. The activities of the train and locomotives in motion are shown in Table 25, together with the speed of the train during the operation. It should be noted that the speeds shown are the maximum speeds reached by the moving train, locomotive or shunting locomotive. It is inevitable that a train will accelerate at the beginning of its journey and decelerate at the end. The acceleration coefficient is 1 m/s^2, while the deceleration coefficient is 2 m/s^2.

Table 25 Data for the moving tasks in the marshalling yard

Position	Operation	Speed (m/s)
Before arrival yard	Train arriving, selecting a free track and driving to the track	9.7
Between arrival yard and classification yard	Line locomotive leaving the arrival yard	5
	First shunting locomotive coming to the end of the train	5
	Shunting locomotive pushing the train to one of the hump	1.94
	Wagons rolling over the hump to reach the track based on their destination	1.39
	Shunting locomotive going back to its waiting position at the beginning of the arrival yard	5
Between classification yard and departure yard	Second shunting locomotive coming to the end of the formed train	5
	Shunting locomotive pushing the train to one of the free track of the departure yard	1.39
	Shunting locomotive going to back to its waiting position at the beginning of the classification yard	5
After departure yard	Line locomotive coming at the beginning of the train	5

	Fully formed train leaving the yard	5

6.1.4 Assumptions

In order to simulate the impact of DAC Type 4 and DAC Type 5 on yard capacity, certain assumptions were made when creating the AnyLogic model. The assumptions regarding DAC Type 4 and Type 5 relate to the duration of coupling and decoupling. The second column in Table 22, Table 23, Table 24 was used to assume the duration of these activities. Based on the duration of manual coupling and decoupling, the times for DAC type 4 and type 5 were proposed based on the opinion of the experts involved in WP19. These times were assumed due to the differences between DAC type 4 and DAC type 5, which come with automatic functions of DAC type 5. For the purpose of this deliverable with experts in WP19, it was assumed that:

- **DAC type 4 is without automatic uncoupling, parking brake, automatic bleeding**
- **DAC type 5 is equipped with all devices/functions.**

Reminder: this "DAC5" configuration hypothesis goes beyond "EDDP DAC Basic Package" which consists of DAC, hybrid coupler, 400V AC electrical energy system, Single Pair Ethernet communication system, train composition detection, train integrity and safe train length determination, automated brake testa and automated uncoupling .

Therefore, the time difference was defined in the third and fourth columns of Table 22, Table 23, Table 24. The coupling and decoupling activities and their duration with DAC type 4 and DAC type 5 as well as the manual coupling and decoupling activities and their duration were summarized in Table 26**Error! Reference source not found.**. summarizes the pure times for coupling/decoupling activities. However, the time required for staff to walk alongside the train from the first to the last wagon has been taken into account in , Table 23, Table 24 on the basis of the trains indicated in Table 28**Error! Reference source not found.** in the case of manual coupling/decoupling and manual decoupling with DAC Type 4.

Table 26 Coupling and decoupling activities and their durations

	Manual coupling and decoupling	**DAC Type 4**	**DAC Type 5**
Coupling time per wagon	1 minute	0 minutes	0 minutes
Decoupling time per wagon	0.8 minute	0.2 minutes	0 minutes
Decoupling line loco	1.5 minutes	1.5 minutes	0.2 minutes

Coupling line loco	0.8 minutes	0.1 minutes	0.1 minutes
Decoupling shunting locomotive	1 minute	0.8 minutes	0 minutes
Coupling shunting locomotive	0.1 minutes	0.05 minutes	0.03 minutes

It was also assumed that we have one shunting locomotive in the arrival yard and another in the classification yard. Initially, it was determined that a single shunting locomotive would be sufficient for the arrival yard. The use of a second engine could shorten the overall time, but the impossibility of using two humps at the same time argued against the use of a second engine for this section of the marshalling yard. Similarly, a single shunting locomotive is used to transport vehicles from the marshalling yard to the departure yard.

Before the AnyLogic simulation, the characteristics of the trains and wagons were assumed in a model based on the opinion of the experts involved in WP19 (see Table 27**Error! Reference source not found.**). In base scenario i.e standard length of trains the arrival of the trains at the beginning of the marshalling yard is characterized by the fact that a train with 26 wagons in base scenario, including a locomotive, arrives every 8 minutes until the arrival yard is full. At this point, a new train arrives every time a track becomes available. It is important to emphasize that a single track must always remain unoccupied in order that the shunting locomotive can return to the start of the arrival yard. The length of the train was determined on the basis of a 640-meter-long train with 24-meter-long wagons each. This ensures that the total length of the train never exceeds the shortest track in the arrival yard. The interval between arrivals was determined based on the time required to serve the trains in the marshalling yard. The frequency of arrivals would lead to conflicts if trains were to arrive more frequently. The composition of the train is randomly selected from a set of five possible destinations, while the distribution of trains is determined from these destinations, with 20% of the trains coming from each destination: Stockholm, Oslo, Gothenburg, Trelleborg and the rest of Europe.

The length of each wagon was standardized to 24 meters, and a distinctive colour scheme was introduced to differentiate the wagons depending on their destination. On arrival, the train is automatically assigned to a free track. The first track to be checked is the lowest one. If it is free, the train moves onto this track. If it is not free, the train checks the upper track. If necessary, the train checks the second track from below, then the second track from above and so on. The aim is to divide the trains evenly between the upper and lower parts of the arrival yard, with the middle track reserved for the shunting locomotive.

For the classification tracks, the two smallest tracks in the middle are reserved for the locomotive leaving the arrival yard and for the return of the second shunting locomotive. The three upper tracks of the classification yard are intended for the maintenance of locomotives, while the three lower tracks are reserved for the maintenance and storage of wagons. A total of 24 tracks are therefore available for classification purposes. To comply with the above figures, nine tracks are used for the classification of trains destined for the rest of Europe, while seven tracks are used for the classification of trains terminating in Stockholm. Three tracks are reserved for trains to Oslo, while another three tracks are reserved for trains to Gothenburg. Finally, two tracks will be reserved for the classification of trains to Trelleborg. The classification strategy foresees the use of a second shunting locomotive after completion of the first classification track to couple all the wagons and then take the newly formed train to the departure yard. This process is initiated as soon as the classification track is deemed to be fully utilized, leaving a minimum safety margin. In the meantime, if other wagons with the same destination arrive at the classification yard, they will be directed to another designated track. It is important to emphasize that the decision as to whether a train is ready to proceed to the next stage depends solely on its length and the length of the track, and not on the number of wagons it consists of.

Table 27 Characteristics of the wagons and trains for standard and longer train length

	Base scenario (without DAC)	Longer trains scenario
Wagon type	intermodal wagon	intermodal wagon
Wagon length	94.7 inch (24.05 m)	94.7 inch (24.05 m)
Number of wagons	26	30
Train length	640 m	740 m

Regarding the departure tracks, it should be noted that the number of departure tracks is half the number of usable classification tracks. Consequently, a train that is on one of the top two usable classification tracks will travel to the top departure track, while a train that is on the third or fourth usable classification track from the top will travel to the second departure track, and so on. An exception to this rule is that the sixth usable classification track from below leads to the fourth departure track from below instead of the third, as there is no direct route between the two tracks. The optimal strategy at this point is to have a locomotive take the lead position in the train as soon as the train is ready to leave the yard. The model was developed to represent the behaviour of trains within a marshalling yard and not their interactions with other trains on the wider network. Therefore, possible conflicts with other trains outside the yard are not considered in this study.

6.1.5 Developped Scenarios

To examine the marshalling yard and the impact of new technologies on the time it takes for a train to pass through, six different scenarios were created to assess the benefits of different improvements to the marshalling yard.

- **The first scenario is a basic scenario in which all coupling and decoupling operations are performed manually**.
- **The second scenario assumes that DAC type 4 is implemented on the wagons and the times for coupling the wagons are eliminated, while the time for partially automatic decoupling of the wagons is partially reduced.**
- **The third scenario assumes the introduction of DAC type 5, in which all times associated with coupling and decoupling activities are removed.**

The first three scenarios were based on standard length trains. As DAC enables longer freight trains, longer trains were assumed in the fourth, fifth and sixth scenarios and all these longer train scenarios were also tested. In all of these scenarios, it was assumed that the trains arriving at the marshalling yard have the characteristics described in Table 28**Error! Reference source not found.**. Each of the scenarios was carried out in a 10-hour simulation analysis. In the first hour of the simulation, the arrival yard was filled with trains, assuming that trains arrive every 8 minutes. After the arrival yard was filled, the trains began to be pushed over the classification hump.

The six scenarios can be divided into two categories. The first three scenarios involve trains with 26 wagons (640 meters in length), while the second category includes trains with 30 wagons (740 meters in length) (see Table 27**Error! Reference source not found.** for more details). The second category is about the length of the trains, because not all tracks in the arrival yard can accommodate a train 740 meters long. The aim is to evaluate the advantages of allowing longer trains to enter the marshalling yard.

Table 28 Scenarios for simulation with AnyLogic

Scenario	*Scenario 1*	*Scenario 2*	*Scenario 3*	*Scenario 4*	*Scenario 5*	*Scenario 6*
Characteristic of the scenario	Manual coupling and uncoupling standard length train	DAC4 standard length train	DAC5 standard length train	Manual coupling and uncoupling longer train	DAC4 longer train	DAC5 longer train
Maximum number of wagons per train	26	26	26	30	30	30

6.2 Results

The results of the AnyLogic simulation show the number of trains that are handled in the arrival station, pushed over the hump and assembled in the classification yard, as well as the number of trains that are ready for departure after each simulation hour.

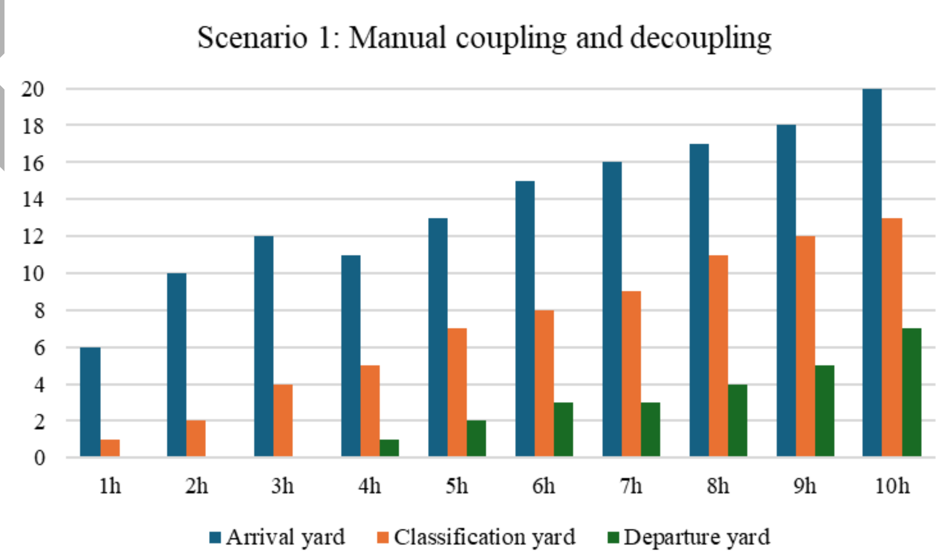


Figure 5 Number of trains in yard with manual coupling and decoupling

Figure 5 hows the number of trains with manually coupled and decoupled wagons in each yard after each hour of the simulation. As can be seen after one hour of simulation, six trains have passed through the arrival yard and the composition for one train has been prepared in the classification yard. The first train to depart from the departure yard was after four hours.

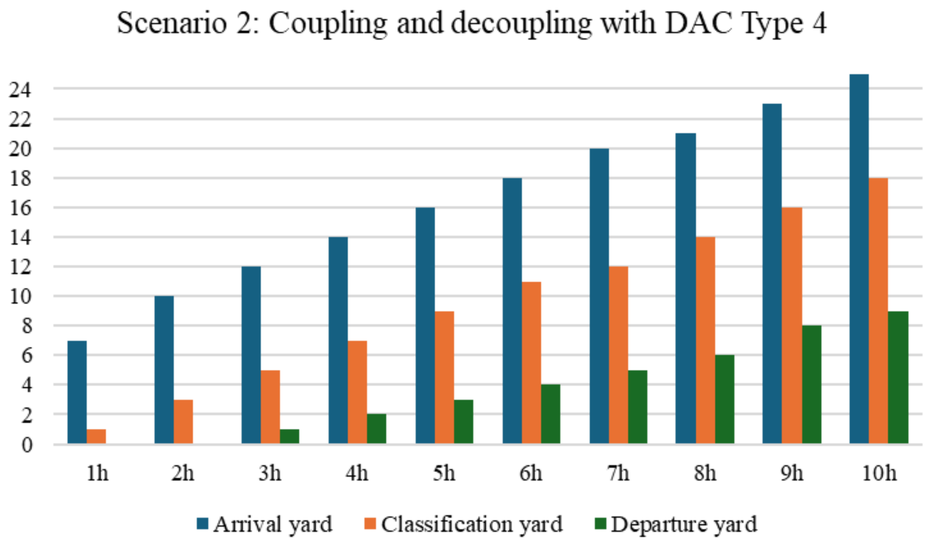


Figure 6 Number of trains in yard with coupling and decoupling by DAC Type 4

Figure 6 shows the results of the simulation assuming that the wagons of inbound and outbound trains in the marshalling yard are equipped with DAC type 4. For the simulation, the assumed duration of the processes specified in the tables (Table 22, Table 23, Table 24) has been taken into account. Compared to the previous scenario, **Error! Reference source not found.** shows that the first train is in the departure yard after the second hour of the simulation. In addition, compared to the previous scenario, one more train can be seen at the arrival yard after the first hour of the simulation. At the end of the simulation, 25% more trains can be seen in the arrival yard, 38% more trains in classification yard compared to manual coupling and decoupling of the wagons (**Error! Reference source not found.**). It can also be seen from the results that nine trains have departed, an increase of 29% compared to the number of trains in the previous scenario (**Error! Reference source not found.**). The main reason for the increased number of handled trains is the reduction in time for coupling and decoupling with DAC type 4.

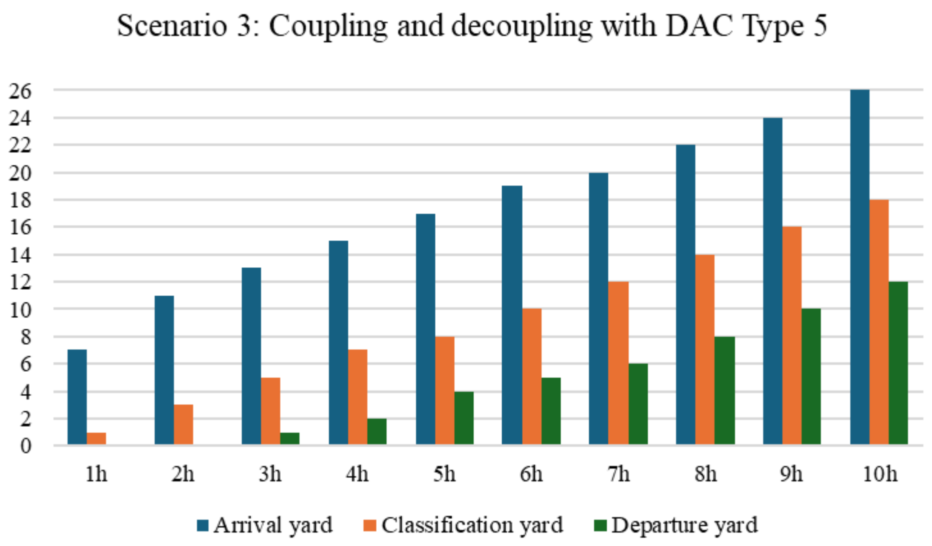


Figure 7 Number of trains in yard with coupling and decoupling by DAC Type 5

The results of the simulation model assuming that the trains are equipped with DAC type 5 are shown in Figure 7**Error! Reference source not found.**. The figure shows that the number of trains was higher than in the two previous scenarios. At the end of the simulation, there were 30% more trains in the arrival yard 38% more trains in the classification yard compared to the manually coupled and decoupled wagons. In addition, twelve trains had departed, which corresponds to an increase of 71% compared to the first scenario (Figure 5**Error! Reference source not found.**).

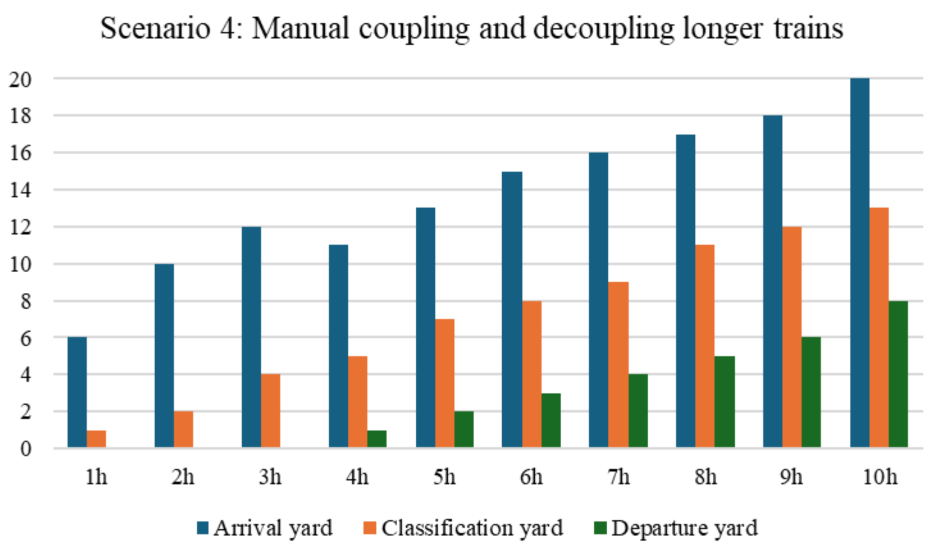


Figure 8 Number of longer trains in yard with manual coupling and decoupling

Since DAC allows longer trains, with Anylogic the number of longer trains processed in the marshalling yard has been analysed. Figure 8**Error! Reference source not found.** shows the results in relation to the longer trains that were manually coupled and decoupled. Compared to the first scenario in **Error! Reference source not found.**, the number of trains in the arrival yard and in classification yards was the same at the end of the simulation. Nevertheless, one more train is recorded in the departure station at the end of the simulation.

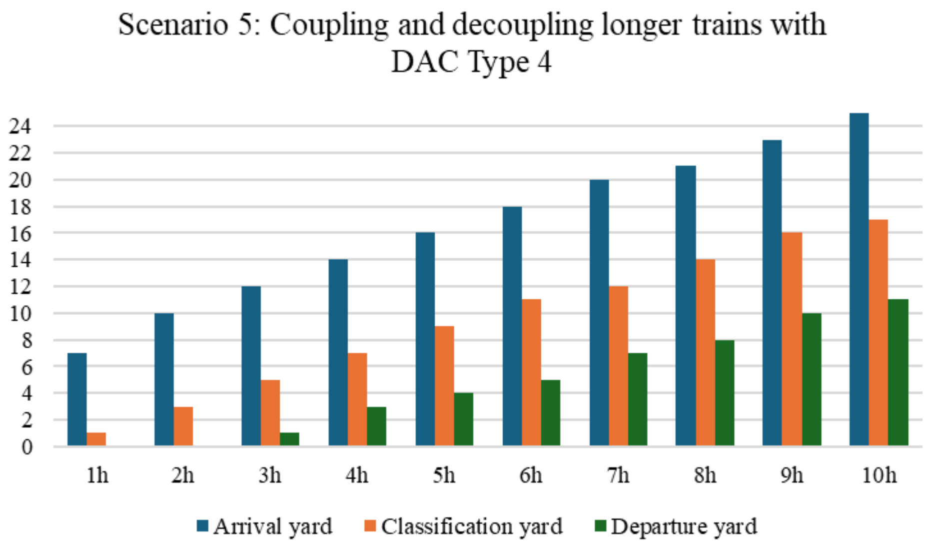


Figure 9 Number of longer trains in yard with coupling and decoupling by DAC Type 4

Figure 9 shows the number of longer trains in which the wagons are coupled and decoupled with DAC type 4. From the analysis of the results, the number of trains is higher compared to the number of longer trains that were manually coupled and decoupled in **Error! Reference source not found.**. Compared to the number of standard-length trains with DAC type 4, two more trains were detected in the departure yard at the end of the simulation.

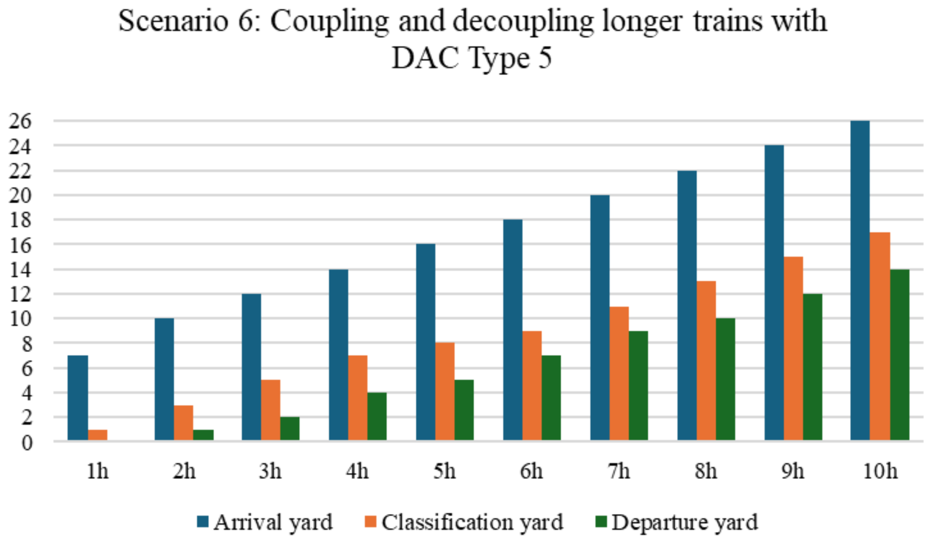


Figure 10 Number of longer trains in yard with coupling and decoupling by DAC Type 5

The number of longer trains increased in all three yards with DAC type 5 (see Figure 10**Error! Reference source not found.**). The results show that compared to the number of longer trains that were manually coupled and decoupled, six more trains were prepared for departure at the end of simulation. Compared to longer trains equipped with DAC type 4, three more trains were recorded in the departure yard. In addition, compared to the standard train length with DAC type 5, two more trains were recorded in the departure station at the end of simulation. Compared to manually coupled and decoupled trains with standard length, as many as seven additional trains were recorded in departure yard at the end of simulation.

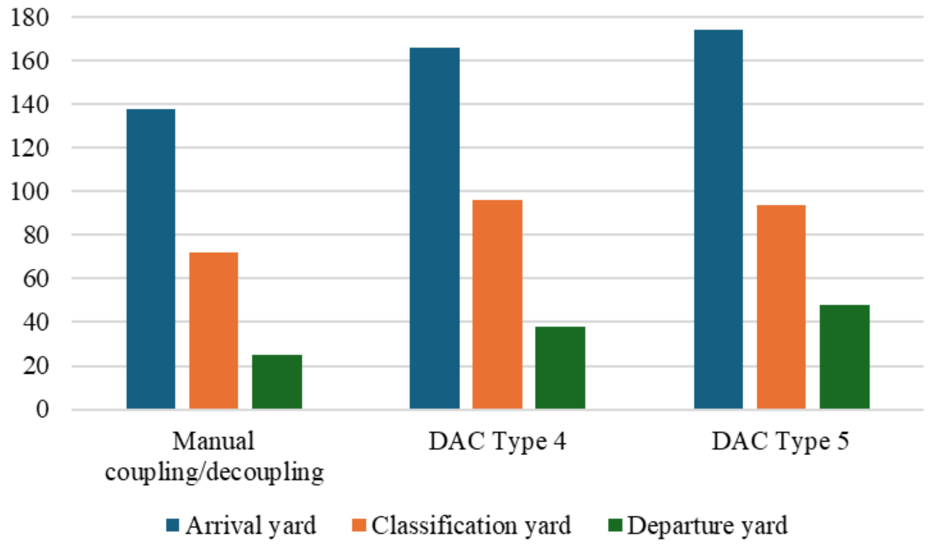


Figure 11 Summary of number of trains in each yard at the end of the simulation

The total number of trains in each marshalling yard with manual coupling/decoupling, DAC Type 4 and DAC Type 5 at the end of the simulation, i.e. after 10 hours of train handling in the marshaling yard, is shown in Figure 11**Error! Reference source not found.**. As can be seen the number of trains with DAC Type 5 increases. The increase can be observed in all yards, with a significant increase in the departure yard. The figure shows that the number of trains in the arrival yard is even higher when switching from manual coupling/uncoupling to DAC Type 5.

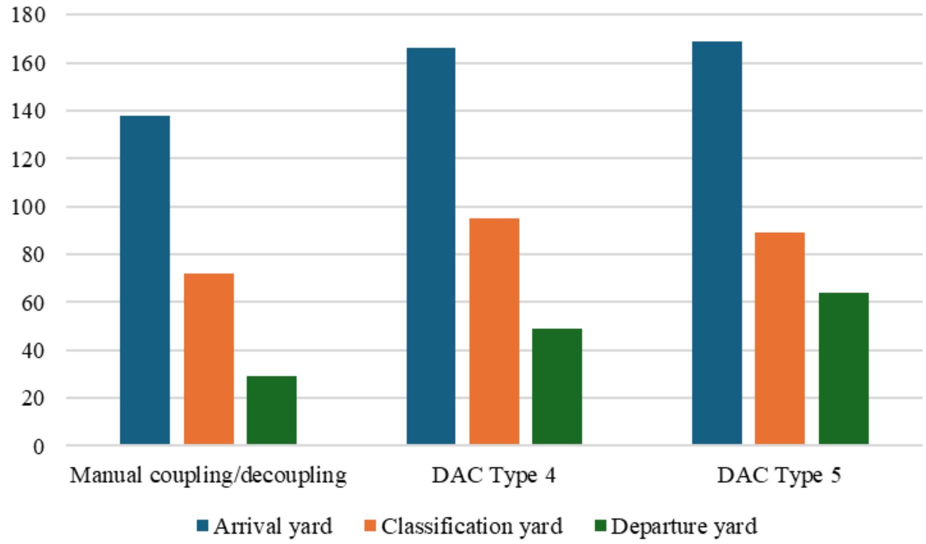


Figure 12 Summary of number longer trains in each yard at the end of simulation

The overall results for a number of longer trains in the marshalling yard are shown in Figure 12**Error! Reference source not found.**. Similar to the results shown in the previous figure, a higher number of trains can be achieved with DAC type 5. The increased number of trains can be seen in all yards. However, it should be mentioned that in this case the number of longer trains is limited by the infrastructure conditions, i.e. the length of the tracks in all yards.

6.2.1 Benefits in yards results

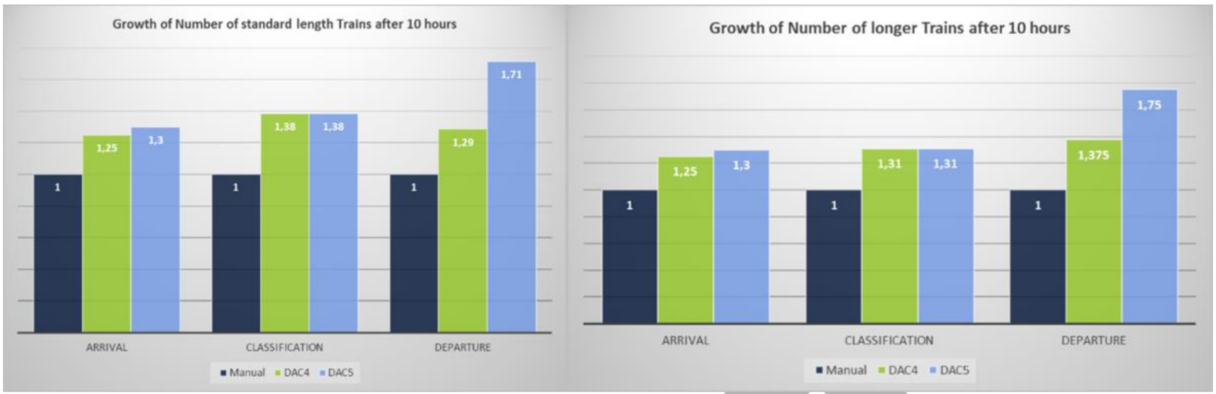


Figure 13 Growth of number of trains after 10 hours

The implementation of Digital Automatic Couplers (DAC) presents significant opportunities for enhancing train yard operations. **DAC Type 4**, with its partial automation, increases the number of processed trains by **29%** in the departure yard. However, **DAC Type 5,** with full automation capabilities, further boosts throughput by **71%** in the same yard, demonstrating its higher efficiency.

Despite these advancements, challenges remain. **Arrival yard capacity bottlenecks** and the limitations imposed by fixed track lengths and available capacity on the main tracks need to be addressed to fully realize the potential of these technologies..

6.3 Open Points

The use of DAC can induce new Bottlenecks in the MY	With AnyLogic, it is not possible to increase the flow rate due to the number of tracks in the arrival bowl. We have done the maximum that is possible. Take a look at **Error! Reference source not found.**. If we have an empty track in the arrival yard, we insert a new train. Therefore, the first bottleneck in all cases would be the arrival yard.
Shunting locomotive speed	The assumption is 1.97 m/s pushing the train to the hump that speed can reach 4 m/s on any other MY that figure may induce a different behaviour in terms of saturation

7 Conclusions

This document constitutes **Deliverable D19.1: LCC and Benefits Inputs to CBA Phase 1** of the ERJU Flagship Area 5 project, FP5-TRANS4M-R. It summarizes the results from **Task 19.1**, focusing on providing inputs for the cost-benefit analysis (CBA) work package of the EDDP, as outlined in the Grant Agreement.

The primary objective of this report is to present preliminary cost and benefit assessments related to the EDDP DAC basic package , with a particular focus on the following phases:

- **supply and installation costs**
- **Utilisation phase**: acquisition and maintenance costs
- **Disposal phase**

These cost estimations were developed based on assumptions informed by inputs from various stakeholders. Through this process, a rough estimation of the DAC's life cycle cost has been established. At this stage, the aim is to provide indicative trends rather than definitive estimates.

DAC transport and installation Costs	Supply Costs	• Estimated cost in euros for transporting all DAC units according to the favored EDDP deployment scenario : **26 € per DAC or 52 € per equipped wagon**
	Installation Costs	• Total installation cost for a wagon with UIC-installation space, Type: vertical support, 2 Axles: **2 012 €** • Total installation cost for a wagon with UIC-installation space, Type: vertical support, 4 Axles: **2 111 €**
DAC acquisition and utilisation costs	Acquisition costs	• Average acquisition cost for the wagon coupler part (including scaling factor): **11 014 € / coupler** • Average acquisition cost for the wagon CCU part (including scaling factor): **8 064 €** • Average acquisition cost for the locomotive hybrid coupler part (including scaling factor): **30 831 € / coupler**

		• Average acquisition cost for the locomotive LCU / MCU part, without the unit power supply system (including scaling factor): **9 783 €**
	Maintenance costs (for a 30 years lifespan)	• The cumulative cost for the coupler part per DAC is **364 € / year** (224 €/year for spare parts, 110 €/year for human resources, and 30 €/year for corrective maintenance) • The cumulative cost for the CCU part per DAC is **319 € / year** (266 €/year for spare parts, 23 €/year for human resources, and 30 €/year for corrective maintenance) Some provided operations are synchronized with overhaul inspection of the wagons to avoid additional shipments and downtime costs
	Disposal benefits	• The end-of-life recycling of a DAC could yield a **benefit of over 300 €/wagon**, excluding battery resale.
Capacity Benefits in Yards		• **DAC Type 4 increases processed trains between 25 and 38%** depending on the train length and the part of Marshalling Yard considered • **DAC Type 5 provides higher results with increases between 30 and 75%**

The analysis highlights a significant disparity in the maturity levels of various DAC components. The coupler component, especially for wagons, demonstrates a much higher maturity level compared to the CCU and LCU/MCU. This difference leads to notable variances in acquisition cost estimates provided by manufacturers, particularly for the CCU and LCU/MCU, complicating accurate cost detailing.
Due to the even lower maturity level of FDFT-components for locomotives at this stage, it has not yet been possible to assess the costs associated with the energy supply system or installation costs.

The costs assessment has the following limitations:

- quality of the data, temporal scope of the projections, and necessary arbitrations in case of conflicting data;
- uncertainties related to design, manufacturing, component costs, and operational behaviours coming from the current pre-industrialization phase

- assumptions for the migration phase based on current data, with uncertainties regarding planning, number of production sites, and installation costs only estimated for wagons equipped with the UIC installation space[3].

A more detailed analysis of the benefits associated with the DAC will be conducted in the next deliverable of WP19. This will incorporate insights from the demonstration trains, scheduled to begin operations in the second half of 2025. These outcomes are expected to refine the cost assessments and provide a clearer picture of the DAC's overall value proposition.

[3] The UIC installation space is the place reserved to the installation of the draft gear part of the DAC under the frame of the wagon

8 Appendices

Appendices summary:

8.1 E-coupler cost assessment

8.2 Context of the analysis for the benefits in yards

8.3 Production capacity table based on favored EDDP migration scenario

8.4 Maintenance cost table

8.5 ADIF study on Iberian gauge impact on DAC (chapter 6 to 8)

8.1 E-coupler cost assessment

8.1.1 Introduction

8.1.1.1 Context

The work presented in this document was carried out by IKOS Consulting as part of a service contract with SNCF Fret for a European project.

Context of the mission

In TRANS4RM-R project, Fret SNCF has been entrusted the lead of Work Package 19 that is named "Input for Cost-Benefit Analysis." WP19 started in January 2023 and will last until March 2026.

The Work Package 19 tasks are :

- delivering two successive reports in March 2025 and January 2026 based on costs from suppliers and costs and benefits from TRANS4RM-R demonstrators (Switzerland, Italy, Sweden, Austria, Germany)
- supporting TRANS4RM-R project by providing cost assessment of possible technological options.

As part of the cost assessments of technological options, IKOS worked on 2 prototype electrical couplers (e-couplers).

The e-coupler part of the DAC is the physical component of each DAC that connects energy and data through the connection of several connectors put in the same box.

The support action provided by IKOS will contribute to support decision-making of the project between both e-couplers prototypes with the aim to select one final prototype based on confidential input from DAC suppliers.

The 2 prototypes were designed by Voith and Knorr-Bremse.

Voith e-coupler prototype

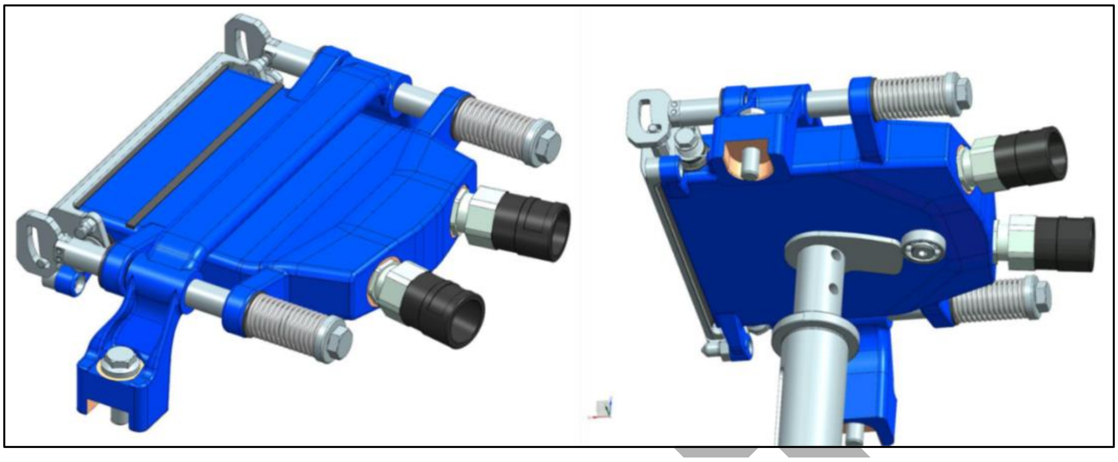


Figure 14 Voith e-coupler prototype (Source: Voith)

The Voith solution works as follows:

- During mechanical coupling, the central pivot of the Scharfenberg system head rotates. This rotation causes a cam under the e-coupler to rotate, releasing the compression springs. The e-coupler moves forward.
- As the e-coupler moves forward, the lid is opened by movement of pins within a guiding lane.
- When the coupler head is mechanically decoupled, the central pivot will return to its initial position, driving the cam and compressing the springs to return the e-coupler to its retracted position.

The special feature of this mechanism is that the e-coupler is dependent on the mechanical coupling, so the e-couplers cannot be coupled until the mechanical part is coupled.

Knorr-Bremse e-coupler prototype

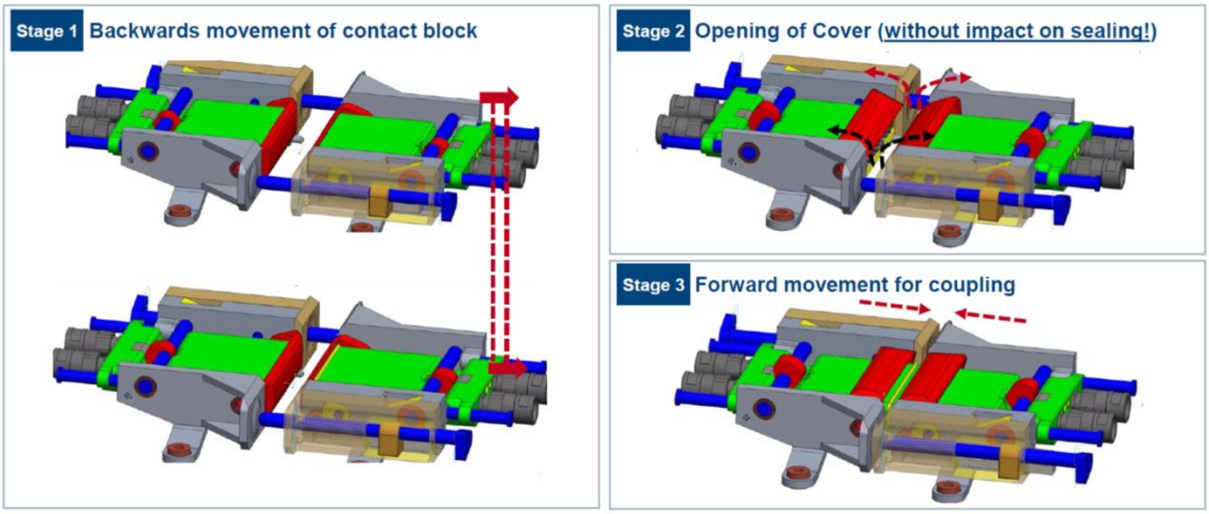


Figure 15 Knorr-Bremse e-coupler prototype (Source: Knorr-Bremse)

The Knorr-Bremse solution works in 3 stages:

- When 2 wagons are coupled, the first part to come into contact in the e-coupler is the plunger. As the plunger is pushed in, it first moves the contact block backwards, creating a gap between the contact block and the lid.
- Then, in the 2nd stage, the translation of the plunger opens the lid.
- In the 3rd stage, the end of the piston's translation will release the compression springs moving the contact block forward to allow the 2 e-couplers to be coupled.

During decoupling, tension springs allow the plunger to retract, reversing the 3 stages.

The special feature of this mechanism is that the e-coupler is independent of the mechanical coupling, and the system is entirely driven by a gearbox that works thanks to the plunger.

8.1.1.2 Objectives

The main objective of IKOS is to compare the costs of the 2 prototypes and to present the results as an element for decision-making between the 2 solutions.

To achieve this objective, the main elements were as follows:

i. **Confidentiality of submitted costs:**

- Suppliers submit their costs confidentially to IKOS. They present the overall costs and may provide details to explain the calculation methods.
- IKOS will not communicate the costs presented by the suppliers.

- Only the percentage difference between the costs will be communicated.

ii. **Types of costs:**

- Acquisition Cost: This cost corresponds to the cost of the e-coupler for the supplier. It is a set of production costs and supplier prices. It is not the market price.
- Maintenance Cost: This cost corresponds to all the preventive maintenance costs for an e-coupler over its entire lifespan. This cost does not include corrective maintenance costs.
- Overall Aggregated Cost: This cost corresponds to the total cost of the e-coupler, i.e., the sum of the acquisition cost and the maintenance cost.

iii. **Information from Suppliers to IKOS:**

- Suppliers thus communicate to IKOS three types of overall costs, as well as the methods used to calculate them:
  - An overall cost of the acquisition of an e-coupler
  - An overall cost of the maintenance of an e-coupler
  - An overall aggregated cost of an e-coupler

iv. **Information from IKOS to Work Package 19 (WP19):**

- IKOS transmits to WP19 the percentage differences between the two e-coupler prototypes:
  - A percentage difference in the acquisition cost of an e-coupler
  - A percentage difference in the maintenance cost of an e-coupler
  - A percentage difference in the overall aggregated cost of an e-coupler.
- These percentages will not be presented in a fixed format, but as a range of 5% percentages (e.g.: 1-5%; 6-10%; 11-15%; etc).

8.1.1.3 Caveats

Before presenting the calculation hypotheses and the results obtained, it is crucial to highlight that these results should be interpreted with caution. They are based on several estimations made by the suppliers to deduce the costs of a final product from a prototype.

Therefore, this analysis based on approximations in several key areas:

- **Design**: The design of the prototypes does not exactly reflect the one of the final products. Modifications are necessary to ensure that the designs of both prototypes fully meet the technical requirements of the operators.

- **Manufacturing Processes**: The methods used to manufacture the prototypes likely differ from those used for the final products. Suppliers had to estimate manufacturing costs based on their experience with other products.
- **Component Costs**: The costs of certain parts have been calculated based on the current prices of their suppliers. Today, depending on the historical products of each of the 2 companies, the prices of their suppliers can vary between the 2 for equivalent parts.
- **Mechanical behaviour over time**: Regarding mechanical fatigue and maintenance, suppliers have relied on laboratory tests to simulate real-life operating conditions. However, these tests cannot perfectly reproduce real-life fatigue and operational constraints.

In summary, although these analyses provide important insights, it is essential to consider them as estimates based on current data and not as exact representations of the cost of the final products.

8.1.2 Analysis hypotheses

To ensure that the calculation conditions were the same for the 2 suppliers, hypotheses were defined. These hypotheses were discussed and validated by the project members.

8.1.2.1 Operational hypotheses

Two operational hypotheses have been defined for calculating costs:

- **Operational hypothesis 1**: The lifetime of the e-coupler is 30 years, with 4,500 couplings over 6 years.

  Source of the hypothesis: D5.2 DAC specification of FP5 TRANS4M-R
  "The service life of the digital automatic coupler for wagons is defined as 30 years under the premises that all necessary maintenance and overhaul have been carried out. Based on 70 000 km per years, 3 coupling cycles per day, 250 operation days per year."
- **Operational hypothesis 2**: The coupling speed is between 0.6km/h and 12 km/h with an average of 5/6 km/h.

  Source of the hypothesis: D5.2 DAC specification of FP5 TRANS4M-R
  "Coupler shall be designed for the following operational procedures:
  a. During normal operations on straight tracks the minimum impact speed shall be 0.6 km/h up to an impact speed of 6 km/h.
  b. A maximum impact speed of 12 km /h shall not be exceeded.
  c. In all other infrastructural conditions like curves, s-curves the maximum coupling speed of 5 km/h shall not be exceeded.

Collisions (impact speed) above 12 km/h is considered an incident and above 18 km/h an accident. In all cases of collisions (impact speed) above 12 km/h appropriate steps shall be taken according to the user manual."

8.1.2.2 Acquisition hypotheses

One acquisition hypothesis has been defined for calculating costs:

- **Acquisition hypothesis**: The number of e-couplers is based on serial condition with 50,000/55,000 e-couplers per year.

  Source: Suppliers (Voith & Knorr-Bremse)

Scope of analysis

To calculate the acquisition cost, a detailed list of the components to be considered was established for each of the two prototypes. As the exact number of electrical contacts required was not defined, suppliers were asked to consider two scenarios: one with 8 contacts and another with 12 contacts. For each prototype, costs will be evaluated and presented for both configurations.

As illustrated in the tables below, certain elements such as electrical pins and all electrical components (cables, hoses, etc.) are identical for both prototypes. To ensure a fair comparison, the costs associated with these common components have been harmonised in collaboration with the two suppliers, guaranteeing an identical value for these items in both cases. This harmonisation of costs for common parts enables a more

Table 30 List of components for the Voith prototype

accurate and balanced assessment of the total acquisition cost for each prototype.

VOITH - Part name	Individual costs	Common costs
E-coupler housing incl. lid and roll	X	
Rail	X	
Bracket	X	
Cover	X	
Cam	X	
Pin block	X	
Pins (8 and 12)		X
Cables & flexible hoses		X

Table 29 List of components for the Knorr-Bremse prototype

KNORR-BREMSE - Part name	Individual costs	Common costs
E-coupler housing	X	
Gear	X	
Plunger	X	
Cover	X	
Cam	X	
Pin block	X	
Pins (8 and 12)		X
Cables & flexible hoses		X

8.1.2.3 Maintenance hypotheses

For the assessment of maintenance costs, a detailed list of maintenance operations to be considered was developed. Initially based on the maintenance procedures for e-couplers on passenger trains, this list was then adjusted to take account of the particularities of freight trains. This adaptation process was carried out in consultation with operators and suppliers, to ensure a comprehensive and relevant approach.

This list of maintenance operations forms the foundation on which the maintenance costs of each prototype will be calculated. The methodology used for this calculation will be detailed in the section dedicated to maintenance costs. It should be noted that operations relating to electrical components are considered identical for both suppliers, meaning that the cost of these operations will be the same for both prototypes.

The table below provides a complete overview of the various maintenance operations envisaged.

Table 31 List of maintenance operations for the e-coupler

List of operations	Intervention components	Details
Visual inspection	**Electrical coupler**	Visually check for deformation of the e-coupler, e-coupler cover and guide rails and visually check that the coupling fixing screws are present and not loose.
Cleaning and degreasing	**Electrical coupler**	Clean the guide rails, electrical contacts, and frame gasket with a degreasing agent.
Examinations, tests and inspections	**Mechanical part**	Check for signs of impact, deformation and breakage on connecting rods, bearing rings, guide rails, centring pin and bushing, cover, coupling body and joints. Check presence and effectiveness of fasteners on cover, insulating block, guide rails, connecting rods and joints. Assessment of the condition of the frame joint. Check for cuts, cracks or deformation of the frame seal. Check the centre distance between the axle and the centring sleeve using a gauge. Check the position of the coupler in relation to the front plate by placing a depth gauge on each side of the e-coupler.
Examinations, tests and inspections	**Checking cover position**	Measure the distance between the top of the body of the e-coupler and the top of its cover when the cover is closed, using a ruler.

Examinations, tests and inspections	**Electrical part**	Research into contacts: breakage; oxidation; deformation.
Lubrication - Greasing	**Electrical coupler**	Grease the following components: the guides of the e-coupler and the links of the e-coupler cover.
Exchange	**Frame seal**	Removing the old frame seal and installing and lubricating the new one.
Exchange	**Cover (Lid)**	Removing the old cover (lid) and fitting the new one.
Exchange	**Mechanical spare parts**	Removing small mechanical parts (spring, centering devices...) and fitting the new ones.
Exchange	**Electrical coupler**	Removing the coupling and installing the new one, including checking the position of the cover and lubrication.
Major overhaul	**Electrical coupler**	Major overhaul of the e-coupler
Exchange (Common operation)	**Data contact**	Removing data contacts (Male/Female contact) and installing new ones.
Exchange (Common operation)	**Power contact**	Removing power contacts (Mobile/Fixed contact) and installing new ones.
Exchange (Common operation)	**Electrical parts**	Removing electrical parts and installing new ones.

8.1.3 Cost assessment

8.1.3.1 Acquisition cost

Graphic

Based on the data provided by Voith and Knorr-Bremse, we were able to establish the difference in acquisition costs between the two prototypes. To ensure the reliability and comparability of the costs proposed by the two suppliers, an in-depth review was carried out by IKOS. To do this, each supplier provided IKOS with details of their costing methodology for each component, enabling an accurate and fair analysis.

The results of this comparative analysis are illustrated in the graph below. This visualisation provides an immediate understanding of the cost differences between the prototypes, facilitating decisions and subsequent discussions.

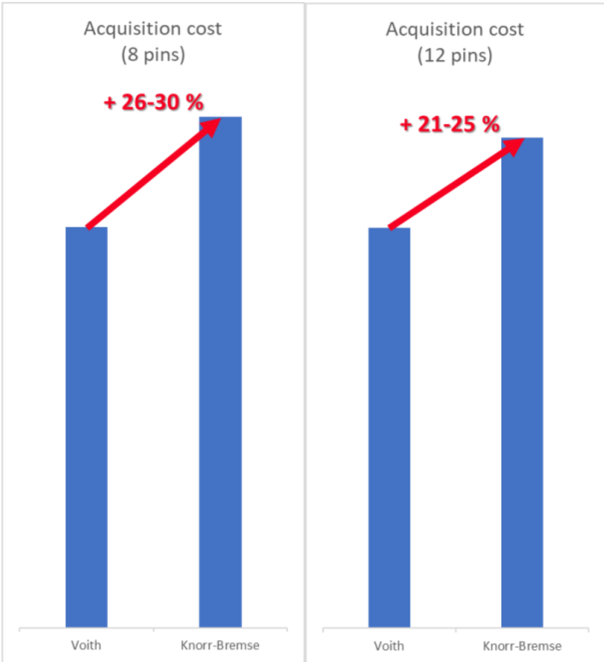


Figure 16 Acquisition cost difference between the 2 prototypes

For acquisition costs:

- For an e-coupler with 8 pins: Knorr-Bremse's solution is 26 to 30% more expensive than the one from Voith.
- For an e-coupler with 12 pins: Knorr-Bremse's solution is 21 to 25% more expensive than the one from Voith.

Suppliers have associated comments to better explain their acquisition cost.

Comments from Knorr-Bremse

"Comments Acquisition Cost (for IKOS and for external)

- KB design optimized for **Life Cycle Cost** with extremely robust design - potentially higher acquisition cost due to robustness will be **recovered over lifetime** (less maintenance, less repairs)
- KB design with **unique protection** against 400-Volt (add. cost for feature)
- Acquisition cost streamlined via Knorr-Bremse high volume **automotive production approach** (Commercial Vehicles Division), **highly automated** production and high-volume **truck & rail global supply chain, as DAC e-coupler technology fits to Knorr-Bremse core competency**
- Calculation based on ongoing **cost-optimization (suppliers, production, design, material, technology…)**

- Main **cost drivers** are:
  - **Over-dimensioned prototype system (life-cycle-test currently at 37 years and still running, test planned up to 40-50 years)**
  - Choosing a very robust 3-stage gear/cam mechanism to streamline Life Cycle Cost via **robust protection**, **highest IP class** (IP 65/66)* and **optimized wear** (e.g. on sealing which allows **3-year exchange interval)**
  - Selection of **system fulfilling highest protection against 400-Volt** via plunger & gears, independent from coupler head locking mechanism (= independent from unreliable uncoupling of second coupler, independent from trigger bar opening, …)
  - **Extreme protection** to avoid impact from external influences (e.g. heavy plate and structural parts, fully enclosed operating system)
- The additional features (400 Volt safety & Extreme robustness) account for roughly **20-25%** of the cost of the total e-coupler (resp. roughly 50% of the mechanical parts only)"

Comments from Voith

"Qualitative comments for others

- Cost based on manufacturing technologies with high quantities
- Contact technology and service capability (quick and save exchange) based on proven and reliable design from passenger coupler business since decades
- Additional function – locking device to hold e-coupler in case of missing similar e-coupler
- Voith calculation also includes overhead for assembly and material
- Less forces due to the actuation concept and no lateral forces on contacts
- Minimum amount of parts - Low total cost of ownership + compact design"

8.1.3.2 Maintenance cost

Calculation method

To estimate maintenance costs, IKOS has developed a precise calculation methodology, based on the exhaustive list of maintenance operations previously defined. This methodical approach consists of several key steps:

1. **Details of maintenance operations**: Each supplier was required to specify and explain the frequency and duration of each maintenance operation, as well as the immobilisation time of the wagon if the operation required a visit to the workshop. This stage is crucial for assessing the operational impact of each operation.

2. **Calculation of the cost of the operation**: Based on the frequency and duration of each operation, the suppliers were able to calculate the associated cost. This calculation includes the cost of the human resources and spare parts required. To harmonize calculations, hourly costs for maintenance technicians have been established using an average based on data supplied by 3 European operators. These costs are 50 €/hour for a level 2 maintenance technician, 65 €/hour for a level 3 maintenance technician, and 80 €/hour for a level 4 maintenance

List of operation	Intervention components	Frequency	Duration	Immobilization Cost (if it is in a workshop)	Intervention cost (human resources + spare parts)	Cost over 1 year	Cost over 30 years
Visual inspection	Electrical coupler						
Cleaning and degreasing	Electrical coupler						
Examinations, tests and inspections	Mechanical part						
Examinations, tests and inspections	Checking cover position						
Examinations, tests and inspections	Electrical part						
Lubrication - Greasing	Electrical coupler						
Exchange	Frame seal						
Exchange	Cover						
Exchange	Mechanical spare parts						
Exchange	Electrical coupler						
Major overhaul	Electrical coupler						
Exchange (Common operation)	Data contact						
Exchange (Common operation)	Power contact						
Exchange (Common operation)	Electrical parts						

External cost hypotheses	
Standard technician (maintenance level 2)	50 €/h
Qualified technician (maintenance level 3)	65 €/h
Specialized technician (maintenance level 4)	80 €/h
Wagon	25 €/day

→ Hypotheses of an average EU cost

Information communicated to the project member
Information communicated to IKOS
Undisclosed information

Annual cost of maintenance	Total cost of maintenance

technician, with an estimated daily cost of 25 € for a wagon. Using these average costs for both suppliers ensures a common and fair basis for calculation.

3. **Presentation and confidentiality of information**: The table below details the information that suppliers had to communicate to IKOS, as well as that which they could keep confidential. This distinction ensures both the transparency required for cost evaluation and respect for the confidentiality of suppliers' sensitive information.

This methodology enabled IKOS to obtain an accurate and comparable estimate of maintenance costs for each prototype, facilitating a complete analysis and informed decision-making.

Graphic

Figure 17 Table to help with maintenance cost calculation

Based on the data provided by Voith and Knorr-Bremse, we were able to establish the difference in maintenance costs between the two prototypes.

The results of this comparative analysis are illustrated in the graph below. This visualisation provides an immediate understanding of the cost differences between the prototypes, facilitating decisions and subsequent discussions.

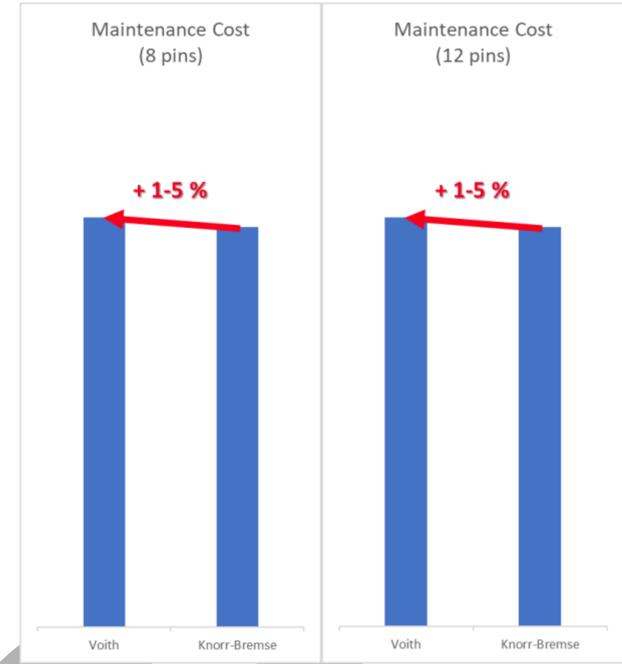


Figure 18 Maintenance cost difference between the 2 prototypes

For maintenance costs:

- For an e-coupler with 8 pins: Voith's solution is 1 to 5% more expensive than the one from Knorr-Bremse.
- For an e-coupler with 12 pins: Voith's solution is 1 to 5% more expensive than the one from Knorr-Bremse.

Suppliers have associated comments to better explain their maintenance cost.

Comments from Knorr-Bremse

"Comments Maintenance costs (for IKOS and for external)

- Knorr-Bremse E-coupler designed to optimize **Life Cycle Cost** (e.g. extreme protection/ enclosed operating plunger-gear-mechanism designed for >>30-years/ unique 3-stage-mechanism with highest IP class and w/o pull-over effect on sealing/ enclosed system w/o greasing or exchange of parts outside of overhaul)

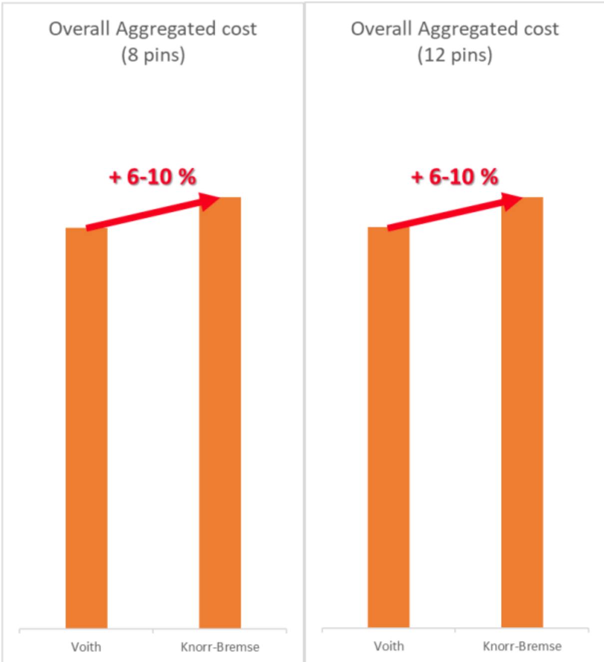
- Additionally, there will be **less accidents and unexpected damages** due to robustness.
- **Preventive Maintenance and Overhaul Scheme**:
  1. **Yearly-Check-Up** of e-coupler on train (visual inspection of mechanical parts and pins/ electrical parts, check for signs of impact, deformation etc., quick cleaning, …)
  2. **Regular exchange of sealing** (3-year interval, on train, only possible due to 3-stage-mechanism)
  3. **No other regular exchange of parts or greasing outside of overhaul.**
  4. **Regular bigger** check of electric parts, esp. Pins (6-year interval, on train or in workshop when whole DAC has light overhaul)
  5. **2x main overhaul/ exchange with refurbished e-coupler** → to reduce stand-still of wagon exchange instead of overhauling in workshop is advised by Knorr-Bremse (12-year interval, on train or in workshop when whole DAC has main overhaul)
- Exchange intervals are based on **life-cycle test in KB lab** (**life-cycle-test currently at 37 years and still running, test planned up to 40-50 years** since significant wear is not yet visible – details see test report) and field experience (esp. TrainLab & DAC4EU)
- Times are based on real measured time in workshop, future improvements are considered based on known and communicated optimizations (e.g. less screws to install cover)"

Comments de Voith

"Qualitative comments for others

- All values based on service and maintenance concept for already running CargoFlex customer project since 2021
- Service intervals 3, 6 and 12 years
- No immobilization cost because of replacement concept
- Not necessary to use grease (no toothing)
- Design optimized for service capability – fast exchange of components even in operation of the wagon
- Worldwide Voith service network for couplers
- Almost all operations can be done by trained technicians
- No special expensive tools needed"

8.1.3.3 Overall aggregated cost



Graphic

By analysing the acquisition and maintenance costs provided by the two suppliers, we were able to calculate the overall aggregate cost for each of the two prototypes. This assessment includes both the initial investment and recurring maintenance costs, providing a complete view of the total cost over the life cycle of the prototypes.

The comparison of the aggregate global costs of the two prototypes is clearly illustrated in the graph below.

This approach not only provides an in-depth understanding of the financial implications of each prototype, but also provides a solid basis for strategic decisions regarding the adoption of one or other of the solutions.

For overall aggregated cost costs:

- For an e-coupler with 8 pins: Knorr-Bremse's solution is 6 to 10% more expensive than the one from Voith.
- For an e-coupler with 12 pins: Knorr-Bremse's solution is 6 to 10% more expensive than the one from Voith.

Figure 19 Overall aggregated cost difference between the 2 prototypes

8.2 Context of the analysis for the benefits in yards

8.2.1 Marshalling yards

The still insufficient efficiency and punctuality of rail freight services is a source of dissatisfaction among rail customers and also a major obstacle to attracting new rail freight flows or customers. Automation and/or optimization can therefore bring a significant contribution by increasing the cost competitiveness of rail freight activity (Deliverable 2.2 IP5 ARC project, 2017). Serving as a vital facilitator for further digitalisation and automation of the European rail system the introduction of a Digital Automatic Coupling (DAC) is seen as a key enabler for improving transport quality and reducing operating costs - with the potential to digitise and automate operational processes in all European rail freight companies and their facilities in the future (Köning, 2020). DAC presents a distinctive opportunity to revolutionise European rail freight, plays a crucial role in overhauling rail operations management and serves as the cornerstone for climate protection and economic advancement, enhancing the capacity on open rail lines and within freight nodes such as marshalling yards to achieve the modal shift of freight from road to rail.

Marshalling yards are important freight hubs in the end-to-end rail freight logistics chain. They play an important role in rail freight transport and their efficiency has a significant impact on the travel time of freight trains (Deleplanque et al. 2022). Marshalling yards are crucial subsystems of vital importance for (single) wagonload. Marshalling yards can be divided into three categories: Flat yards, gravity yards and hump yards.

- The flat marshalling yards are built on level ground or on a slope that is too gentle to allow the movement of wagons without the use of locomotives. In this case, the freight wagons are transported to their destination with the assistance of a locomotive (Kneafsey, 1975).
- In contrast to the flat-shunted yard, the freight wagons in the gravity yard can be moved by gravity. Nevertheless, this type of yard is still used in some countries for small freight flows, as in many cases locomotives were still needed for shunting, especially with regard to meteorological conditions (Berti, 1959).
- The last type of marshalling yard is the hump yard. It is considered the most efficient form of marshalling yard and is therefore also the most widespread. In contrast to gravity yards, hump yards operate in the same way as gravity yards, with the difference that the descent occurs primarily at a specific section known as the hump. The hump serves as the central device of the marshalling yard and consists of a guide track, which is located on a small hill and onto which a locomotive pushes the wagons. At the arrival yard, at or just before the apex of the hump, depending on the type of wagon, individual wagons or groups of coupled wagons are detached and roll by gravity onto their respective tracks in the classification yard, the area of the yard designated for sorting the wagons (ABC's of Railroading: Terms of the Trade, 1991). As the marshalling yard that is the

subject of this deliverable is a hump yard, a more detailed description will be provided. A hump yard can be represented as depicted in Figure 20**Error! Reference source not found.**. The train arrives and stops at the arrival yard. Subsequently, the Mainline locomotive is detached, as are the freight wagons or a group of freight wagons if some of them are to remain together. When the locomotive is uncoupled from a train upon its arrival at a terminal, it is necessary before the wagons in the train can be shunted to "bleed', or drain, the air from the auxiliary reservoir under each wagon to avoid leakage in the brake pipe. This draining of the brake system has heretofore been accomplished by means of a bleeder valve provided on each auxiliary reservoir. In order to drain the system, it is necessary to open all the valves in the train, which operation consumes a significant period of time. After it, a shunting locomotive then arrives at the tail and pushes the wagons over the hump. The wagons then roll automatically by gravity to the classification yard, where they are sorted according to their destination. The final composition of the wagon set takes place in the classification yard, where the freight wagons are coupled once again. The brakes are also filled with air in the classification yard and tested for safety reasons. As soon as all the necessary tests have been completed, another shunting locomotive is coupled with the wagons. After a further series of tests, the train is then transported to the departure yard. On arrival at the departure station, the shunting locomotive is decoupled and departs. Finally, the line locomotive arrives and is coupled to the train. If the brakes have not been filled with air and tested in the classification yard for safety reasons, this can be done in the departure yard. Once the final brake tests have been completed, the train is ready to depart (Antognoli, 2020).

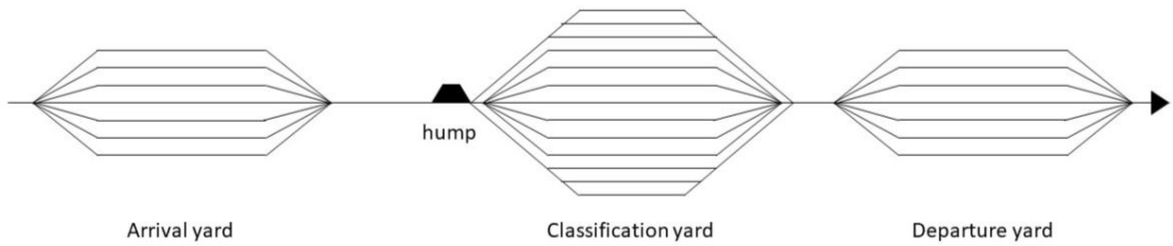


Figure 20 Layout of a Hump yard

For the purpose of this deliverable Hallsberg marshalling yard was selected as a case study to investigate the impact of the implementation of digital automatic coupling (DAC) on the capacity of the marshalling yard. The main reason for choosing Hallsberg is the volume of trains handled, which makes it the largest marshalling yard in Sweden (Antognoli, 2020). Another reason is the various operations that take place in Hallsberg marshalling yard, which are naturally connected to coupling and decoupling. Using the Hallsberg marshalling yard as a case study, the benefits of DAC Type 4 and DAC Type 5 on the capacity of the marshalling yard were evaluated using the AnyLogic simulation tool.

In addition, the same tool was used to compare the positive effects of DAC type 4 and type 5 on the capacity of the marshalling yard with manual coupling and decoupling. The main differences between DAC Type 4 and the existing manual coupling and decoupling are the incorporation of automatic coupling of mechanical, air, power and data bus lines and a manual decoupling system by a lever. In addition to automatic, remote-controlled decoupling, DAC type 5 also includes the automatic coupling of mechanical, air, power and data bus lines, thus enabling a more automated and comprehensive digitization of the marshalling yard (Cantone, 2022).

8.2.2 Brief about Hallsberg Marshalling yard

The Hallsberg marshalling yard is the largest and most important in terms of the number of trains handled in Sweden. It is located at the center of the Swedish rail network as the main hub in the north-south freight corridor and is the most important production site for rail freight transport in Sweden. Due to its geographical location, Hallsberg marshalling yard has a strategic position in the Swedish freight flows and forms an important hub for Swedish rail freight traffic.

International freight traffic with destinations to Germany and Italy, for example, passes through Hallsberg on its way to the connections from the southern part of Sweden to Europe via the Öresund Bridge to Denmark or via the port terminals in Trelleborg and Ystad. The western main line connecting Sweden's two largest cities, Stockholm and Gothenburg, also passes via the marshalling yard.

The Hallsberg marshalling yard is built like a gravity yard, as there is a continuous gradient for the entire yard. In addition, although there are two tracks over the hump in the marshalling yard (or to be more precisely, two tracks over the same hump), only one hump can be used at any one time for safety reasons and because of the track layout.

The owner and operator of the Hallsberg marshalling yard is the Swedish Transport Administration (Trafikverket). The throughput capacity of the marshalling yard is 500,000 wagons/year on a total track length of 60 km with 170 switches. The effective shunting volume of the Hallsberg marshalling yard is 305,000 wagons/year.

8.2.3 Operations in Hallsberg marshalling yard

The operation of the Hallsberg marshalling yard, as any marshalling yard with hump, can be divided into the following activity groups, such as train arrival, hump operations; classification and train departure. When a train arrives, it must be prepared to pass over the hump. The time of the preparation process depends on the number of wagons in the wagon set and takes about 28 minutes for a wagon set of 32 wagons, for example. This activity includes several tasks, which are described in Table 22**Error! Reference source not found.**. The time spent on some operational tasks and the preparation time before the departure of a train are listed in table 23 **Error! Reference source not found.** and Table 24. As presented in Table 22, when a train arrives, it waits for the appropriate signal until it is green, then the wagon set moves to an assigned track in the arrival yard. After parking on the arrival track, the line locomotive at the head of the train is uncoupled and a shunting locomotive is positioned at the tail of the train once the latter is ready for being pushed over the hump. All brakes are then released and checked wagon by wagon. When the time of rolling to the hump comes and the signals show the appropriate sign, the shunting locomotives push the wagons onto the hump and roll either to an assigned classification track or to the mixed tracks. In the Hallsberg marshalling yard, when a wagon set is assembled on a classification track, no wagons from other wagon sets can enter this track. The classification yard therefore requires at least one classification track for each departing wagon set. Before the wagons can leave a track, several tasks must be completed. This means that if a track is full, a minimum time is required before the track is free again. In addition, some of the shunting tasks, such as releasing the brakes, consist of various detailed subtasks. Further information and times for these tasks can be found in the first and second columns in Table 23**Error! Reference source not found.**.

When a wagon set is ready and all the wagons have been assembled, the wagon set leaves the classification yard and goes to an assigned track in the departure yard, where various tasks are carried out to prepare the train for departure. These tasks include, for example, decoupling from the shunting locomotive and coupling to the departure locomotive, checking and testing the braking systems, etc. Further details, including the minimum time for each task, can be found in the second column of Table 24**Error! Reference source not found.**.

8.2.4 Benefits in yards References

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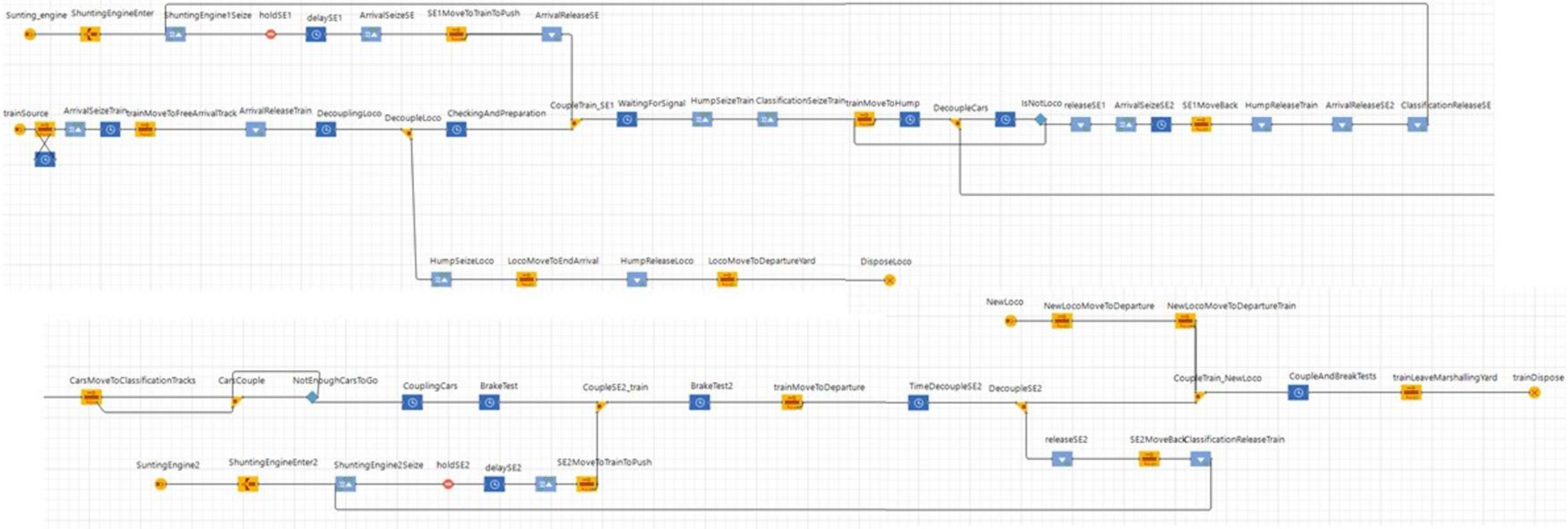

Figure 21 Schematic overview of processes in marshalling yard with AnyLogic model

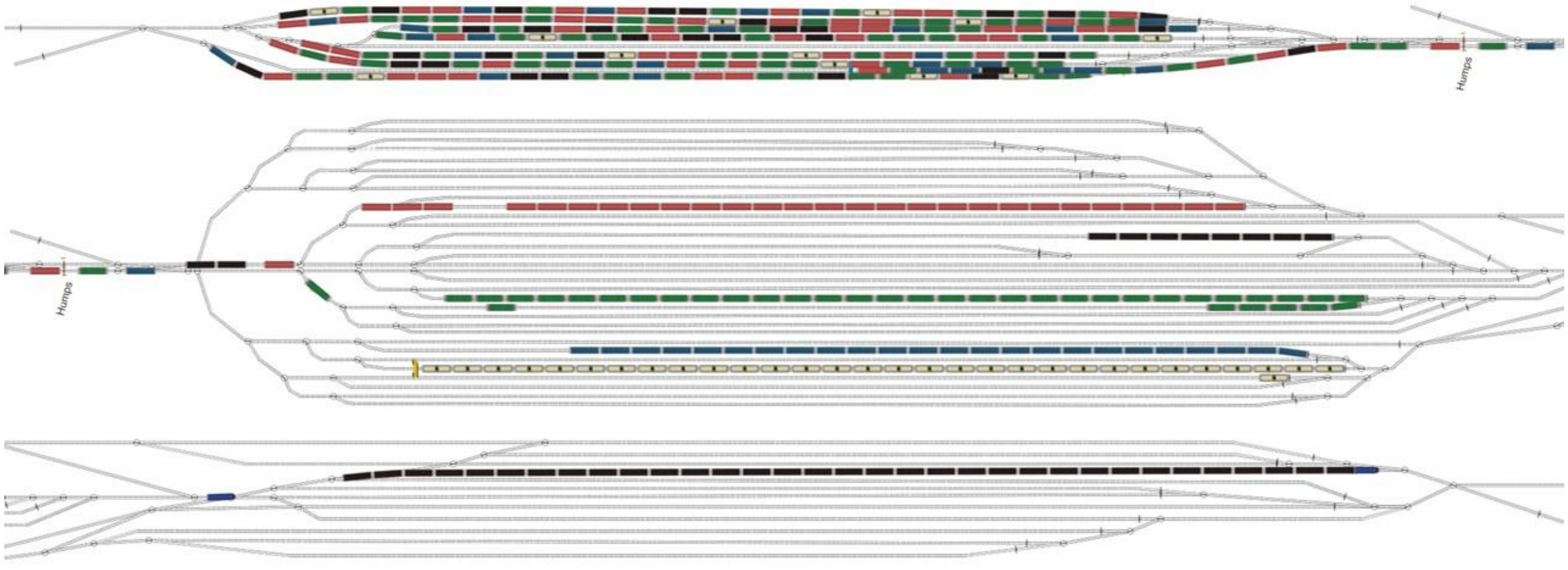

Figure 22 Hallsberg's marshalling yard layout with trains on it

8.3 Production capacity table based on favored EDDP migration scenario:

Variable		2028	2029	2030	2031	2032	2033
SELECTED - SWL wagon - DAC ready - retrofit basic	number of wagons retrofitted as 'DAC ready'	41 000	81 000	122 000	157 000	-	-
SELECTED - SWL wagon - DAC ready - retrofit complex	number of wagons retrofitted as 'DAC ready' - complex retrofit	-	-	-	-	-	-
SELECTED - SWL wagon - DAC ready - new	number of new wagons that are 'DAC ready'	-	1 000	2 000	2 000	-	-
SELECTED - SWL wagon - DAC2 - retrofit basic	number of wagons retrofitted with 'DAC2'	-	-	-	162 000	81 000	-
SELECTED - SWL wagon - DAC2 - retrofit complex	number of wagons retrofitted with 'DAC2' - complex retrofit	-	-	-	-	-	-
SELECTED - SWL wagon - DAC2 - new	number of new wagons with DAC2	-	-	-	-	-	-
SELECTED - ALL wagons - DAC4/5 - retrofit basic	number of wagons retrofitted with 'DAC4/5'	20 800	43 200	64 000	92 800	209 000	322 000
SELECTED - BLOCK wagon - DAC4/5 - retrofit basic	number of wagons retrofitted with 'DAC4/5'	14 300	29 700	44 000	63 800	88 000	110 000
SELECTED - IT wagon - DAC4/5 - retrofit basic	number of wagons retrofitted with 'DAC4/5'	6 500	13 500	20 000	29 000	40 000	50 000
SELECTED - SWL wagon - DAC4/5 - retrofit basic	number of wagons retrofitted with 'DAC4/5'	-	-	-	-	81 000	162 000
SELECTED - ALL wagons - DAC4/5 - retrofit complex	number of wagons retrofitted with 'DAC4/5' - complex retrofit	3 900	8 100	12 000	17 400	24 000	30 000
SELECTED - BLOCK wagon - DAC4/5 - retrofit complex	number of wagons retrofitted with 'DAC4/5' - complex retrofit	1 638	3 402	5 040	7 308	10 080	12 600
SELECTED - IT wagon - DAC4/5 - retrofit complex	number of wagons retrofitted with 'DAC4/5' - complex retrofit	585	1 215	1 800	2 610	3 600	4 500
SELECTED - SWL wagon - DAC4/5 - retrofit complex	number of wagons retrofitted with 'DAC4/5' - complex retrofit	1 677	3 483	5 160	7 482	10 320	12 900
SELECTED - ALL wagons - DAC4/5 - new	number of new wagons with DAC4/5	21 227	41 453	60 680	79 906	101 133	122 359
SELECTED - BLOCK wagon - DAC4/5 - new	number of new wagons with DAC4/5	8 576	16 664	24 272	31 803	40 049	48 210
SELECTED - IT wagon - DAC4/5 - new	number of new wagons with DAC4/5	3 669	7 284	10 836	14 497	18 637	22 899
SELECTED - SWL wagon - DAC4/5 - new	number of new wagons with DAC4/5	8 982	17 505	25 572	33 606	42 447	51 251
SELECTED - loc - retrofit basic	number of new locs with DAC	2 000	4 000	6 000	8 000	10 000	13 500
SELECTED - loc - retrofit complex	number of retrofitted locs with DAC	-	-	-	-	-	-
SELECTED - loc - new	number of retrofitted locs with DAC, requiring additional components as, for instance, there is no installation space	250	500	750	1 000	1 250	1 500
SELECTED - loc - SC operations	number of locs not fitted with DAC (e.g. economically unfeasible), but which can continue operations based on exemption grounds	-	-	-	-	-	-
SELECTED - loc - scrapped	number of locs scrapped due to the DAC implementation (e.g. no alternative use / economically unfeasible)	-	-	-	-	-	-
DELTA WAGONS		86 427	87 327	84 427	93 927	63 027	59 227
DELTA LOCOMOTIVES		2 250	2 250	2 250	2 250	2 250	3 750
TOTAL COUPLERS		172 853	174 653	168 853	187 853	126 053	118 453
TOTAL HYBRID COUPLERS		4 500	4 500	4 500	4 500	4 500	7 500

8.4 Maintenance cost table:

Maintenance interventions		Operational check-up	Examinations, tests and inspections	Small Overhaul	Main Overhaul	Corrective maintenance	Annual maintenance cost of coupler part	Annual net present maintenance cost of coupler part
Peridocity		Every year	Every 3 y	Every 6 y	Every 12 y	Every year		
Human Resource Cost		35	120	37	440	/		
Systematic maintenance Cost		/	/	400	1430	/		
Conditional maintenance Cost		4	40	/	650	/		
Global Cost		39	160	437	2540	30		
Lifespan	1	1				1	69,00	66,99
	2	1				1	69,00	65,04
	3	1	1			1	229,00	209,57
	4	1				1	69,00	61,31
	5	1				1	69,00	59,52
	6	1	1	1		1	666,00	557,76
	7	1				1	69,00	56,10
	8	1				1	69,00	54,47
	9	1	1			1	229,00	175,51
	10	1				1	69,00	51,34
	11	1				1	69,00	49,85
	12	1	1	1	1	1	3206,00	2248,62
	13	1				1	69,00	46,99
	14	1				1	69,00	45,62
	15	1	1			1	229,00	146,99
	16	1				1	69,00	43,00
	17	1				1	69,00	41,75
	18	1	1	1		1	666,00	391,20
	19	1				1	69,00	39,35
	20	1				1	69,00	38,20
	21	1	1			1	229,00	123,10
	22	1				1	69,00	36,01
	23	1				1	69,00	34,96
	24	1	1	1	1	1	3206,00	1577,14
	25	1				1	69,00	32,95
	26	1				1	69,00	31,99
	27	1	1			1	229,00	103,09
	28	1				1	69,00	30,16
	29	1				1	69,00	29,28
	30	1	1	1		1	666,00	274,38
							10935,00	**6722,25**

8.5 ADIF study on Iberian gauge impact on DAC (chapter 6 to 8):

Chapter 6: Effect of different track gauges on DAC retrofitting

6.1 The question of different track gauges

As it is widely known, the conventional track gauge in Spain and Portugal is not the same as that of most of the EU-countries. The track gauge in Spanish and Portuguese conventional tracks is 1,668 mm, while the gauge used in most of the EU-countries and in most of the Spanish high-speed network is 233 mm lesser, precisely 1,435 mm. The 1,688-mm gauge is internationally known as "Iberian gauge" as it is only used in the Iberian Peninsula, whereas the 1,435 mm is known as "international gauge" or "standard gauge".

In Spain, freight trains are dispatched on conventional railway lines in almost 100 % of the cases, so Iberian gauge is the one to be considered when assessing the effect of different gauges on DAC retrofitting. In the case of Portugal, freight trains are always dispatched on Iberian-gauge tracks, so the assessment is perfectly valid for Portugal as well.

This difference in the track gauge raises the following question: If the aim is to develop a standard DAC for all of the EU-members, what are the design implications of this difference?

Giving answer to this question using the Iberian gauge as a reference is the best option in order to get to know the implications since the difference between the standard and the Iberian gauge (with the latter being 233 mm greater) is higher than the difference between the standard gauge and any other specific gauge (excluding metric gauge):

- Ireland: 1,600 mm (165 mm more than the standard gauge).
- Small parts of the Polish, Romanian, Slovakian and Hungarian networks: 1,520 mm (85 mm more).
- Estonia, Latvia, Lithuania: 1,520 mm (85 mm more).
- Finland: 1,524 mm (89 mm more).

Metric gauge (1,000 mm; 435 mm less than standard gauge) is not a widespread gauge in any EU-country. It is relatively common in Northern Spain, although it is mostly used for passenger trains instead of freight trains. In any case, if the gauge effect comparing 1,668-mm and 1,435-mm gauges is noticeable, then metric gauge will be also included in the analysis.

Given that the interaction between the rolling stock and the infrastructure is not the same on straight tracks (straight alignments of the railway layout) as on curved tracks (curved alignments of the railway tracks), both interaction cases are to be considered separately.

After the interaction analysis has been carried out, a discussion on those parameters with a highest impact will be unfolded, which will give rise to conclusions. These conclusions will be presented at the end of the chapter.

6.2 Coupling on a straight track

On straight alignments, wagon coupling by means of DAC is performed in the same way regardless of track gauge. This is so because the fact that the rails are closer or farther to each other does not affect the horizontal centring (and the side movements, in general) of the wagons, which is the most critical parameter in order to enable coupling.

The following drawing depicts the coupling of one pair of identical wagons on an international-gauge track, as well as the coupling of another pair of identical wagons on an Iberian-gauge track. The characteristic dimensions are annotated in the drawing and it must be specified that the rail profile is 60E1 (60 kg/m) according to EN 13674-1:2012+A1:2018 [5], while the wheels are 920-mm nominal diameter ones with a 1/40 tread and flange profile according to EN 13715:2007+1:2011 [6]. It must be noted that the distance between 920-mm circumferences is annotated both horizontally and vertically:

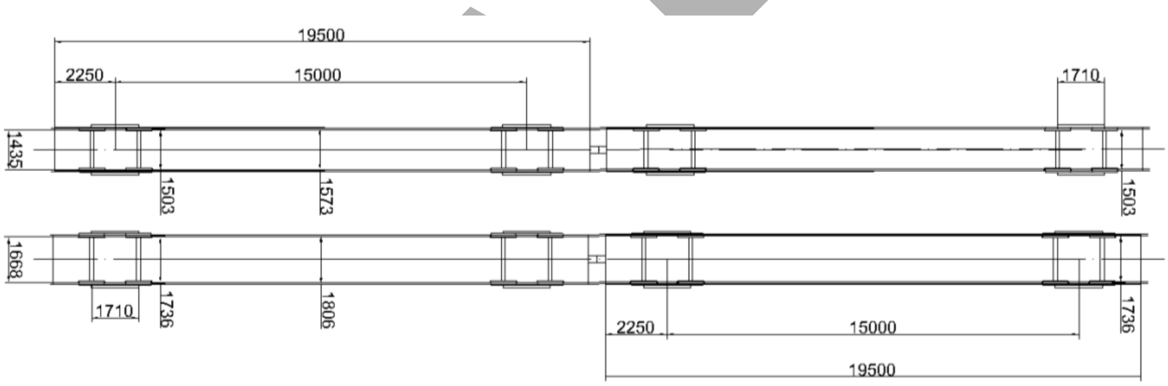

Figure 23 Effect of different track gauges when coupling on a straight track

6.3 Coupling on a curved track

On curved alignments, the rail farther from the curve centre is longer than the rail closer to the centre. This length difference is proportional to the gauge, so as track gauge grows, greater the difference between the rail lengths is. That is the main difference between curves with different gauges.

However, this does not have any effect on how the railway vehicles negotiate curves. If the same wagons as in **Figure 23** negotiate two 300-m curves, each of a different gauge, it can be graphically checked (on a top view, without superelevation, warp nor suspension effects) that the vehicles negotiate them in the same manner, so coupling is unaffected:

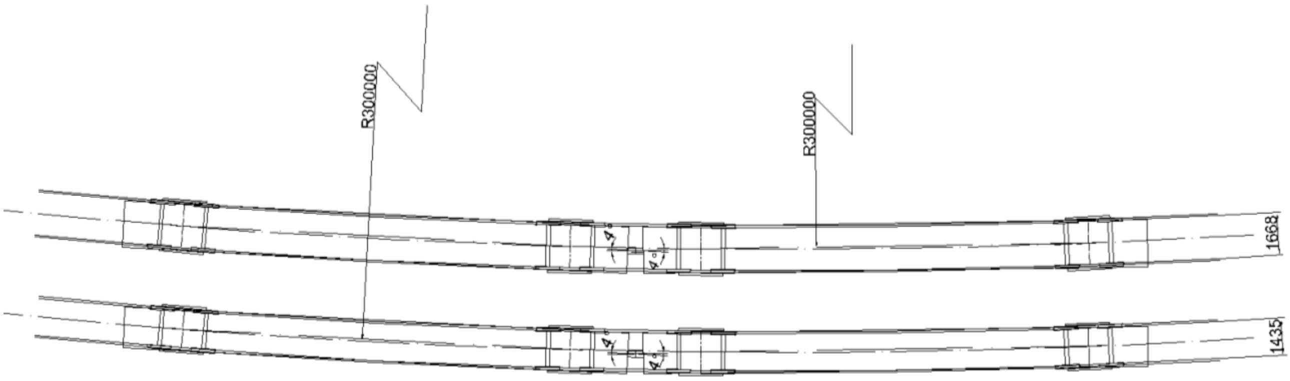

Figure 24 Effect of different track gauges when coupling on a curved track

In both cases, and under the hypotheses assumed, the angular deviation between the axes of the wagon pair to be coupled is found to be equal: 4 º. This means that the easiest way to couple each pair would be a 2 º rotation of both AC's: one of them would rotate leftwards, while the other would do rightwards. This rotation falls into the range of horizontal deflection angle associated with the state-of-the-art AC's. For example, regarding that of the CargoFlex AC (collected in **Table 34**): ±17 º for strokes less than 50 mm and ±12 º for strokes between 50 and 110 mm.

Another important parameter is the horizontal offset or uncentering between the heads of both AC's, which can be accurately computed by means of a formula that takes into account suspension effects. This formula, which allows computing the side movement between the 2 heads, is presented in the UIC 530-1 leaflet [4] and considers that one wagon is located on a straight track, while the other is on a curved track. This is not the case in the current analysis, so the formula requires an adaptation.

If both wagons were situated on a curved track with a constant radius (R), the formula must be suited to that situation, which can be done by adding another term dependent on the curve radius (for the other wagon).

The reduction factor (k) depends on the wagon characteristics, mainly on its suspension. In fact, it differs if bogies are used or not and if the suspension has a slight or noticeable side play [4].

The values for R, a, n come from **Figure 23** and **Figure 24**; the values for q_1 comes from common operating values in the Spanish railway network (this will be discussed later on); the value for q_2 comes from an idealistic assumption; and, finally, the value for k comes from both figures as well, where four-axle wagons with two bogies each are shown, whose suspension is considered to be damped with a slight side play:

Table 32 Input data

Input variable (unit)	Value

$R\ (mm)$	300,000
$a\ (mm)$	15,000
$n\ (mm)$	2,250
$q_1\ (mm)$	3.50
$q_2\ (mm)$	0
$k\ (\phi)$	0.40

When inputting these values, the result obtained is $A = 133\ mm$ that each wagon contributes with a 66.50-mm offset. This horizontal uncentering (133 mm) falls inside the horizontal gathering range of DAC (collected in **Table 34** as well): +275 mm / -370 mm. As a result, coupling is possible for the depicted wagons under the described conditions.

6.4 Discussion upon parameters impact

Even if track gauge seems not to affect wagon coupling, it is necessary to keep researching so as to find that or those parameters with the highest impact.

When a wheelset is running on a straight track and there does not exist any lateral oscillations (hunting oscillation), the wheelset is centered with respect to the track center and its flanges never touch the rails because of a clearance called *flangeway clearance* (ζ) and described in References [7], [8] and [9].

This clearance can be measured by drawing a parallel line to the rolling plane 10 mm below it and measuring the distance between the flange and the rail. On straight tracks, under the conditions stated, the right clearance is equal to the left clearance and their sum is the *track play* (σ). This is also described in the same References.

If a parallel line is drawn 14 mm below the rolling plane, then the track gauge can be measured between the intersection point with rail and the flange point previously used for clearance measurement (despite being 4 mm upwards in vertical). Track gauge may suffer deviations originating at the manufacturing, assembly or usage stages. These deviations are controlled in order to avoid derailment on straight tracks or increases in track play susceptible of worsening lateral oscillations on straight tracks.

The track play can be associated with the gauge and the thickness of the wheel flange along the aforementioned line with a 10-mm offset from the rolling plane downwards. Another parameter worth noting is the rail slant: each of the rail is slanted with a certain inclination (1:x) towards the track centre. The slant angle (γ) is associated with it.

The following drawing depicts two wheelsets running on two different straight tracks:

- On the left, one wheelset is running on an international-gauge track (the wheelset is specifically adapted to this track, so it can be named *international wheelset*). The nominal diameter of its wheels is D and the distance between nominal-diameter circumferences is ℓ. The variables ζ, σ and γ are represented as well.

- On the right, another wheelset running on an Iberian-gauge track (so an *Iberian wheelset*). The nominal diameter of its wheels is also D, but the distance between nominal-diameter circumferences must be longer as the gauge is wider; ℓ'. The clearance and slant variables are also annotated, but with an apostrophe for them to be distinguishable from their international-gauge counterparts: ζ', σ' and γ'.

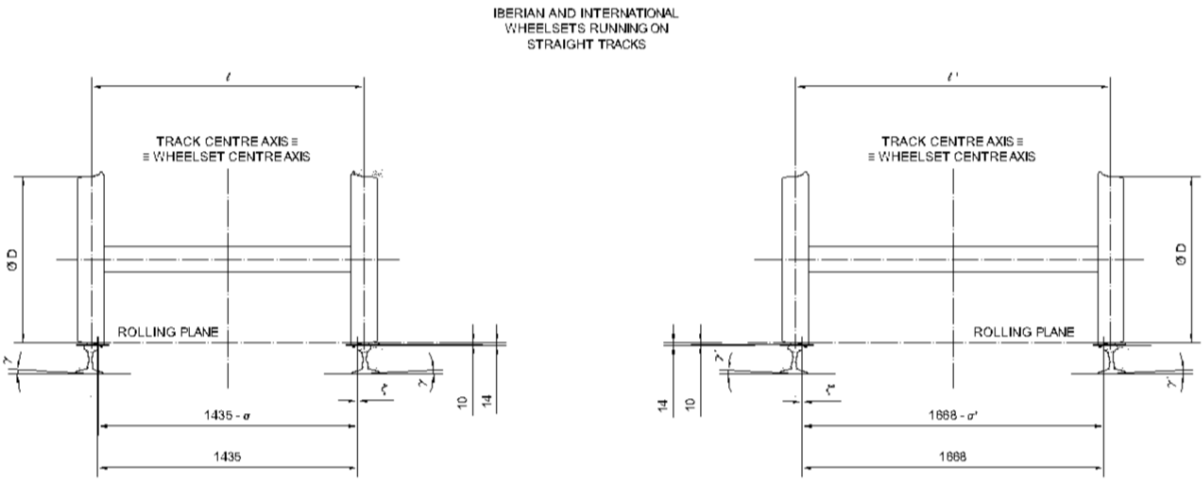

Figure 25 International and Iberian wheelsets running on straight tracks

On the other hand, when a wheelset is running on a curved track, the wheelset experiences a high centrifugal force and tends to go off the track. In order to mitigate this centrifugal force, superelevation is applied: this parameter, denoted with h, is defined as the elevation or height difference between the outer rail and the inner rail. An in-depth description of superelevation is given in NAV 0-2-2.1 technical specification [10], although it must be noted that this specification is designed for Iberian gauge.

Because of superelevation, the rolling plane becomes leant towards the inner part of the curve with a certain angle with respect to the horizontal plane. This angle, denoted with ϑ, can be used to compute superelevation in the current analysis.

The inclination of the rolling plane and the positioning of the contact areas between the wheels and the rails (may they be on the wheel tread or in the wheel flanges) cause the wheelset to tilt, with the result being that the wheelset revolution axis does not remain parallel to the rolling plane. The tilt angle (ϕ) appears between them.

When the curve radius has a reduced value, the flange of the front outer wheel presses against the rail and receives a reaction force from the latter, a lateral force which could prompt derailment by flange climbing. In order to mitigate this effect and facilitate curve negotiation, the track gauge is widened by installing the outer rail a bit farther from the inner rail (the position of the inner rail always remains unchanged).

This gauge increases or widening is denoted with ξ and it is described in depth in NAV 7-3-2.0 technical specification [11], which obliges to apply widening for curves with a radius less than 300 m (tight ones), although it must be noted that this specification is meant for Iberian gauge.

As it happened for straight tracks, track gauge may suffer deviations originating at the manufacturing, assembly or usage stages. These deviations improve curve negotiation when they widen the gauge and they worsen curve negotiation when they narrow it. However, they are sporadic and are eliminated from time to time, so they are not going to be parametrised in the current analysis.

The following drawing depicts two wheelsets running on two different straight tracks:

- On the left, one wheelset is running on an international-gauge track (the wheelset is specifically adapted to this track, so it can be named *international wheelset*). The nominal diameter of its wheels is D and the distance between nominal-diameter circumferences is ℓ. The variables σ, γ, ϕ, h and y are represented as well.
- On the right, another wheelset running on an Iberian-gauge track (so an *Iberian wheelset*). The nominal diameter of its wheels is also D, but the distance between nominal-diameter circumferences must be longer as the gauge is wider; ℓ'. The same variables as in the international-gauge cause are annotated with an apostrophe for them to be distinguishable from their international-gauge counterparts: σ', γ', ϕ', h' and y'.

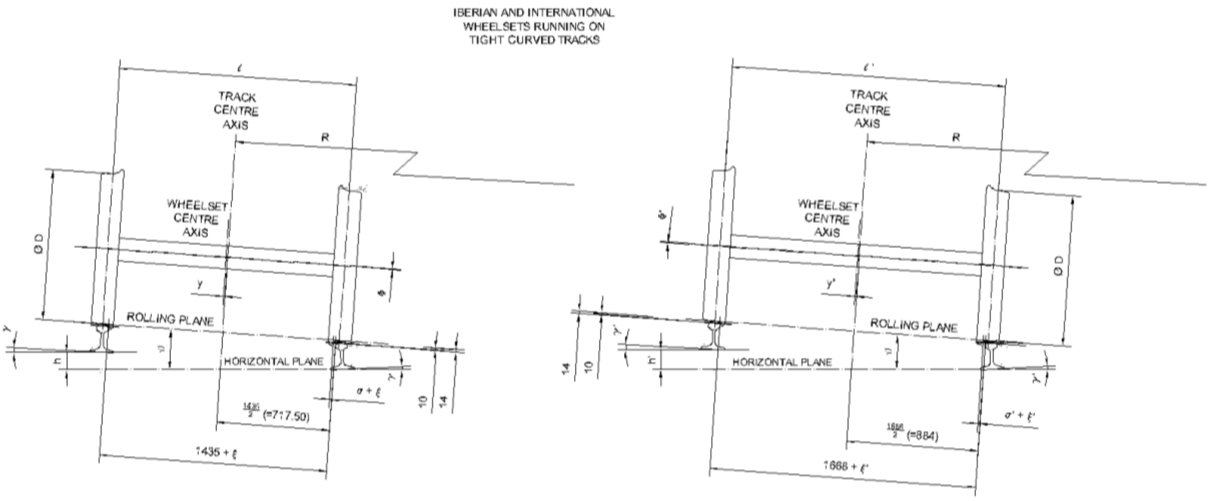

Figure 26 Iberian and international wheelsets running on curved tracks

After such an exhaustive parameters description for both international and Iberian-gauge cases, the impact of each of them is to be assessed, keeping the curve radius, the wheel diameter, the flange thickness and the cant angle the same for both scenarios: $R = 250$ m, $D = 920$ mm, $t = 30.5$ mm and $\vartheta = 4$ º. It is worth mentioning that $\vartheta = 4$ º yields these superelevations: $h \cong 100$ mm (international gauge) and $h' \cong 117$ mm (Iberian gauge).

The next table gathers all of the information, starting with the description of the parameter to be assessed, then continuing with its symbol and its unit, next its value range (with an example), providing the references right after that and ending with the impact assessment:

Table 33 Parameters impact assessment for both gauges

Parameter description	Symbol (unit)	Value range (example)	Reference & company	Impact assessment
Distance between the nominal rolling circumferences for both gauges	$\ell\ (mm)$	1500±3 (1504)	Ref. [12] (value to match the σ used by SNCF)	The distance between the nominal rolling circumferences depends on the wheelset construction and contributes to the determination of the real track play, which makes curve negotiation possible, so it is relevant.
	$\ell'(mm)$	1733±3 (1736)	[N/A] (value to match the σ' by ADIF & RENFE)	
Rail inclination angle for both gauges	γ (º)	1:20 – 1:40 (1:20)	Ref. [13] for all of the EU (Ref. [14] for SNCF and ADIF)	Rail inclination is necessary for distributing the forces transmitted by the wheels at the infrastructure. However, its effect on curve negotiation and coupling is neglible as it does not modify the flange – rail clearances.
	γ' (º)			
Track play for both gauges	$\sigma\ (mm)$	6 – 10 (6)	Refs [7], [8] (Ref. [9] for SNCF)	Track play is fairly influential as it makes curve negotiation possible and, hence, coupling on curved tracks (without track play, the bogies would derail). The value for Iberian gauge is slightly more favourable for coupling.
	$\sigma'(mm)$	6 – 10 (7)	Refs [7], [8] (Ref. [9] for ADIF & RENFE)	
Gauge widening for both gauges	$\xi\ (mm)$	$\begin{cases} 0;\ 300\ m < R \\ 5;\ 200 < R \leq 300\ m \\ 10;\ 150 < R \leq 200\ m \\ 15;\ 120 < R \leq 150\ m \\ 20;\ 100 < R \leq 120\ m \end{cases}$	Ref. [15] for DB – West Germany	Gauge widening is impactful as it facilitates curve negotiation and, hence, coupling (the bogies can better fit to the gauge and the AC's rotate to a lesser extent). The values are based on experience and are not virtually dissimilar for both gauges.
	$\xi'\ (mm)$	$\begin{cases} 0;\ 300\ m < R \\ 5;\ 250 < R \leq 300\ m \\ 10;\ 200 < R \leq 250\ m \\ 15;\ 150 < R \leq 200\ m \\ 20;\ 100 < R \leq 150\ m \end{cases}$	Specification NAV 7-3-2.0 [11] for ADIF	

Lastly, and despite the fact that the buffers are removed before installing DAC (DAC takes over the wagon separation between wagons and energy absorption functions that the buffers had), it is worth checking the UIC 527-1 leaflet [16] as well in order to discuss its technical content:

- Buffer length is different in countries with a different track gauge as Spain or Finland, but the root cause is the wagon width, which depends on the gauge and modifies buffer distance, causing buffer length to adapt.
- The design of S – curves (2 curves linked with a shape similar to that of 'S') does not only depend on the radii of the curves (one of them being in the reverse direction with respect to the other), but also on the gauge. The correct design of S – curves can avoid derailment caused by climbing, a type of derailment happening when the flange of one of the wheels mounted on a bogie presses against the rail so hard that it climbs the rail in the end. It is out of scope to replicate these formulae here, but they are to be briefly explained next.

A first formula computes the arithmetic combination of both radii is equal to or above a certain threshold (0 is its value), then an intermediate straight stretch is required between both curves with the objective of avoiding derailment. If so, another formula is employed so as to compute the minimum length of that stretch.

In both formulae the track gauge (*I*) is inputted in a term with the form (1,470 – I); however, the formulae are not calibrated for Iberian gauge (but could be easily modified by swapping the following values for Iberian-gauge ones) and only work in the range $1{,}440 \leq I \leq 1{,}470$ mm. In fact, what these formulae compute is the offset between the maximum track gauge (1,470 mm) after implementing gauge widening for curves with a very low radius (around 150 m) and considering also track assembly tolerances and the actual track gauge (in the aforementioned range). In other words, these formulae focus on track play (σ).

Again, track gauge does not even affect the negotiation of S – curves, which are the most unfavourable curves as the direction of one of them oppose the other's.

6.5 Conclusions of the analysis

After having found and discussed about those parameters with a highest impact, the following conclusions can be drawn:

1. The study of wagon coupling is associated with the study of curve negotiation. The first phenomenon cannot be understood aside, without the second one.
2. It is not the track gauge that has an effect on curve negotiation and, hence, coupling, but track play.

3. Track play ranges from 6 to 10 mm depending on the value adopted by the infrastructure manager and the rolling stock manufacturers, normally basing on their maintenance experience and stability analyses (hunting oscillations on straight tracks). For instance, SNCF applies 6 mm while ADIF & RENFE apply 7 mm [7], [8], [9].
4. As track play increases, curve negotiation becomes easier and the angle deviation of each of the AC's involved in coupling diminishes.
5. When the railway vehicles are negotiating reduced-radius curves, the wheel flanges press against the rails and those receive a reaction force from these. So when the curves are very tight (those with radii less than 300 m), gauge widening is applied in order to enlarge track play and avoid that the flange of the wheel outer flange presses against the rail aggressively, which could lead to derailment. This facilitates curve negotiation and, therefore, coupling.
6. Gauge deviations originating at the manufacturing, assembly or usage stages should be also taken into account. They are positive for curve negotiation and coupling when they enlarge the gauge and negative when they shrink it. However, this happens with the same intensity regardless of the gauge, so the negative effect is counterweighed in the same way for any gauge.
7. The measures taken to counterweigh the negative effects appearing at the implementation stage consist in designing DAC beforehand with angle and linear tolerances wide enough for making coupling possible in any situation, regardless of gauge.

To end with, these conclusions are really significant as their implication is far-reaching: DAC design and implementation stages will not be affected by the variety of gauges found across the EU, which will not pose any obstacles to it. Hence, a DAC design with wide angle and linear tolerances wide enough is enough for making coupling possible in any situation, regardless of track gauge.

In fact, its implementation will be even possible for metric gauge networks, since the flangeway clearance in this network cannot vary significantly with respect to that of other networks. As a matter of fact, in Spain ADIF manages all of the different networks, RENFE (among other entities) operates vehicles on all of them and the same national or abroad companies manufacture vehicles for all of them.

Chapter 7: Testing in Spain

7.1 Proposed tests

Some tests were proposed by RENFE and ADIF to be executed at the most suitable facilities. It must be noted that the tests are particularly designed to test DAC in unfavourable and degraded situations (if it works in these situations, then it can be assumed that it will also do in the ideal or close-to-ideal ones):

- Coupling and decoupling test with both AC's set at different heights.
- Coupling and decoupling test on an S – curve consisting of 2 linked curves with no intermediate straight stretch in-between.
- Equipment airtightness after coupling test, checking with a sensor the working pressure of the brake pipe.
- Equipment airtightness after decoupling, checking with a sensor the working pressure the working pressure of the brake pipe.
- Coupling test with a wagon whose brake pipe has been depressurized.
- 5 coupling and decoupling tests, consecutive for repeatability checking.
- Electrical conductivity test.
- Coupling at different AC temperatures test.

Despite the impossibility to carry out all of these tests on a single day, given that neither the means availability nor the deadlines allowed carrying them out on a single day, both of the companies involved worked willingly and opened the path for repeating the tests or performing further tests in the future.

In the following sections, the companies involved, the test location and the equipment to be tested are to be defined, providing all of the information required for the full understanding of the tests, which is needed before presenting the results and the conclusions in the ensuing chapter.

7.2 Companies involved

The collaboration and the help of the following entities, listed in alphabetical order, were indispensable in order to perform the tests:

- ADIF: railway infrastructure manager.
- RENFE: railway vehicles operator.
- Talleres Alegría: wagon manufacturer.
- Voith: DAC supplier.

Talleres Alegría made 2 wagons available for the tests: a container wagon and a pocket wagon used on rolling highways. 2 DAC's supplied by Voith were installed on them for the tests described above.

7.3 Test location

The tests were conducted at a factory owned by Talleres Alegría in Lugo de Llanera, a little town in Asturias. The track located inside the factory is divided into 2 stretches:

- 200-m long straight stretch.
- Stretch with a S – curve consisting of 2 linked curves without an intermediate straight stretch: One of the curves is a 75-m radius curve, while the other curve (in the reverse direction) is a 75-m radius curve as well.

It is worth noting that this S – curve is neither compliant with the design specifications gathered in Norma Adif Vía 0-2-2.1 [10] nor UIC 527-1 leaflet [16] as such radii are below the threshold radii above which an intermediate straight stretch between the curves is required. This may be because this section of infrastructure is managed by the factory and not by ADIF (UIC member). It is also likely that a derailment is easier to manage whenever it occurs inside a factory that at an open railway line, as in inside a factory there are overhead cranes that can readily solve the incidence.

7.4 Equipment to be tested

Talleres Alegría installed the AC's on two different types of wagons, both complying with the UIC 530-1 leaflet [4], which made retrofitting easier, verifying the type of DAC is indifferent as to the type of wagon retrofitted.

At this stage, it its necessary to remark that Talleres Alegría is a company exclusively dedicated to manufacturing rolling stock and railway equipment. Although part of its daily activity focuses on design, manufacturing and technical assistance for trackside equipment and for conventional lines, underground systems, tramway systems and high-speed lines; throughout the years the company has diversify its railway business areas.

As for the container wagon, this is the intermodal wagon Sggrss 80', a 6-axle wagon meant for containers and interchangeable units transported on railway lines with a standard track gauge (1,435 mm) or an Iberian track gauge (1,668 mm). The wagon design complies with the TSI -WAG- and EN's and conforms with requirements of IRS 5071-4 for flat container wagons. The wagon drawing (profile and top views) is shown below:

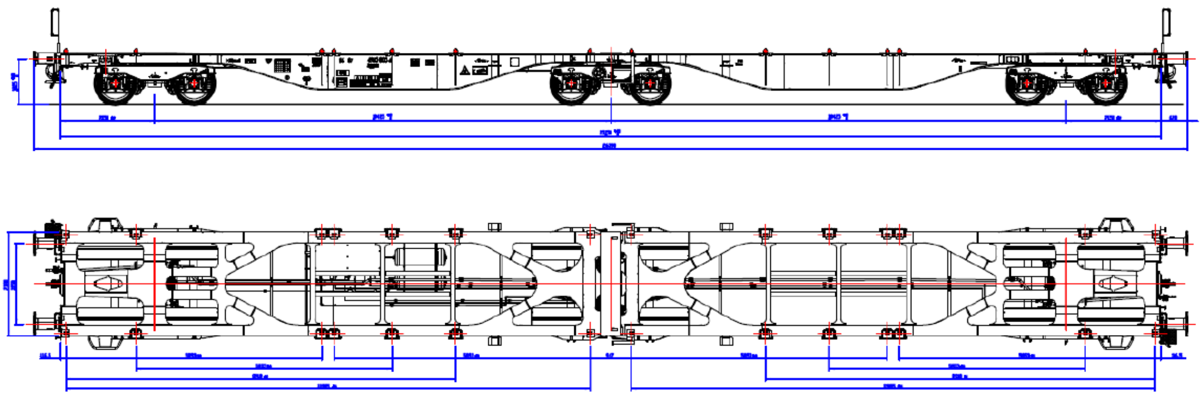

Figure 27 Container wagon for Iberian gauge

As for the pocket wagon, this is the wagon Sdggmrss, a 6-axle wagon meant for craneable semi-trailers transported on railway lines with a standard track gauge (1,435 mm) or an Iberian track gauge (1,668 mm). The wagon design complies with the TSI -WAG- and EN's and conforms with requirements of IRS 5071-4 for flat container wagons. The wagon drawing (profile and top views) is shown below:

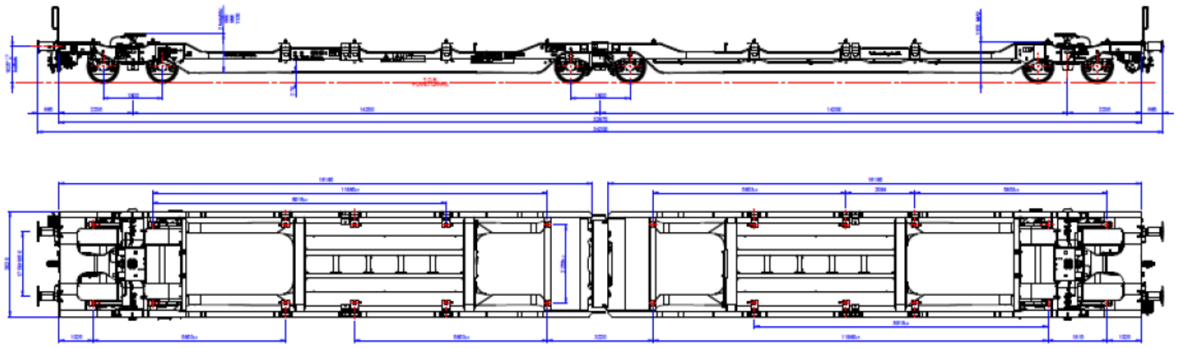

Figure 28 Pocket wagon for Iberian gauge

On behalf of Voith, 2 CargoFlex AC's were supplied, whose main technical characteristics are tabulated in the next table, which provides information on the characteristic, its value, the standards or technical norms with which they comply and also some remarks when needed:

Table 34 Technical characteristics of the CargoFlex AC

Characteristic	Value	In compliance with	Remarks
Admissible force, tension	1,000 kN (yied strength) / > 1,500 kN (rupture load)	EN 12663, UIC 522, UIC 530	Separate load paths for tension / compression (higher fatigue strength); no screw connection in the load path (easy maintenance)
Admissible force, pressure	2,000 kN (yield strength)		
Deflection angle, horizontal	±17 ° up to 50-mm stroke; ±12 ° from 50 to 110-mm stroke	According to diagram UIC 530-1	-
Deflection angle, vertical	±6 °		
Minimum coupling speed	0.6 km/h	-	
Maximum coupling speed	Up to 12 km/h	EN 12663 / category F – I	Impact test in June 2018, reversible energy absorption

Interfaces	According to UIC 530	UIC 530	-
Articulation length	1,000 mm	-	Pivot to coupler face
Gathering range, horizontal	+275 mm / -370 mm	EN 16019 / TSI -HGV- / UIC 522	Interoperability requirements, gathering range requirements from UIC 522
Gathering range, vertical	±140 mm		
Coupling on driving through curved tracks, marshalling humps and ferry ramps	According to UIC 522, chapter 3, requirements	UIC 522	-
Minimum curve radius	R75 m	-	For nearly all standard wagons
Coupler head	Based on Scharfenberg coupler	EN 16019 / TSI -HGV- / UIC 522	Standard throughout the EU
Electric head	400 V AC	-	Optional, also as a retrofit solution
Signal / data transmission	-	-	Power, data, EP brake
Uncouple device	Manual (option: pneumatic)	UIC 522, 2, 1a, 3.2b	Manual uncoupling from vehicle side
Coupler joint	Stabilising linkage, restoring under a compressive loads; coupler to be swivelled manually	UIC 523, UIC 530-2	Reduced risk of derailment; slack in linkage for starting longer and heavier trains with backlash compensation device
Weight	395 kg	-	Same weight as buffer + draw + hook combination
Stroke on draft	110 mm	UIC 524, UIC 530, EN 15227	UIC 524: spring devices for wagons with AC's, reference freight wagon according to UIC
Stroke on buff			

Energy absorption dynamic	70 kJ		524; UIC 530: mounting area / interfaces; EN 15227: optional enhancements to get a crash-proof system
Crash energy absorption (irreversible)	In preparation		
Diameter of brake pipe	1¼“ (31.75 mm)	-	
Pressure in brake pipe	5 bar	EN 16019	
Environmental conditions	-40 °C up to +70 °C	EN 50125-1, class T1	-
Fire protection class	HL2	EN 45545	
Options and additional modules	Manual uncople device with position for marschalling hump, MRP, automatic uncoupling, data & energy transmission	EN 15227, EN 16019, TSI’s, UIC 522	

Chapter 8: Results of testing in Spain

8.1 Test 1 on a straight stretch with both AC’s centered

The objective of this first test was to verify that DAC is capable of coupling both wagons both mechanically and pneumatically:

Figure 29 Coupled wagons

5 coupling tests on a straight stretch at different speeds were performed and in one of the tests the coupling did not suceed. The failure cause of coupling was due to the fact that one of the plates over which DAC is fixed was loose on one of wagons.

The coupling wagon was the right one, while the coupled wagon was the left one. It is worth noting that the coupled wagon (the red one in **Figure 29**) had the brake shoes loosened, something unusual in a normal coupling.

8.2 Test 2 on a straight stretch with both AC's uncentered

Scharfenberg couplers incorporate a guiding horn that facilitates the self-centring of both ends during the linking process, for which there exists a virtual area around which both couplers can approach and reach linkage. This area is cross-hatched in the following cross-sectional view:

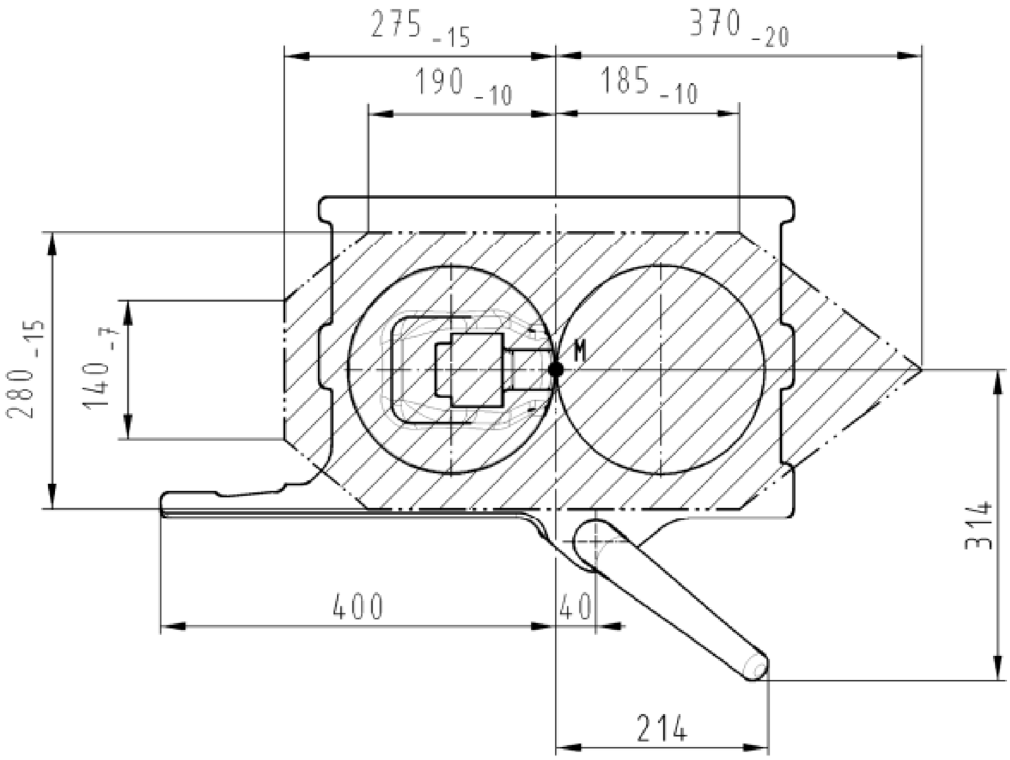

Figure 30 Scharfenberg coupler's virtual area (cross-hatched)

Therefore, for a perfect coupling it is necessary that this device finds itself centred between the tolerances given by the manufacturer.

During testing there was a coupling case out of this theorical area, in which both heads were banged without reaching linkage, yet any damages were not suffered.

Figure 31 Coupling failure

8.3 Test on a curve

In the test on a curve, it was determined that, just as in the test where the AC's were uncentred, it was not convenient to couple und decouple under these conditions. This is why it is recommended coupling and uncoupling on straight tracks, classification tracks more precisely.

It is worth remarking that adjusting the AC's manually, they coupled each other perfectly on the S – curve, composed of a curve and a reverse curve, both with a 75-m radius.

Figure 32 Coupling on a curved track

8.4 Test with the AC's set at different heights

With the purpose of verifying that the height difference in DAC did not generate any coupling distortions, the height of one of them was reduced, while keeping the height of the other one.

The goal of this test is to see which types of wagons with different height tolerances or located on tracks with different gradients could be successfully coupled.

In the next photograph it can be clearly seen that the couplers' guiding horns enable centring the coupling when both AC's are set at different heights:

Figure 33 Coupling with a height difference between the AC's

8.5 Testing conclusions

In the first place, it is necessary to remind and understand that this DAC test has been the first one carried out in Spain for Iberian track gauge. In order to carry it out, 2 wagons provided by Talleres Alegría and 2 AC's provided by Voith were availed.

It can be concluded that DAC is a piece of innovation intending to revolutionise the rail freight transport market so that it becomes much more competitive than road transport, albeit this revolution will arrive in the long run, as it will have to be developed along the train length and speed increases.

Even though tests lacked means (tools, for example), given the lack of a speedometer, barometer for the brake circuit or other devices to broaden the testing perspectives, the overall balance of the tests has been fairly satisfactory.

Several coupling and decoupling processes were undertaken, verifying their right working, as well as some working details which were found surprising, such as the easiness for wagon decoupling or even the self-centring performed by the guiding horns when coupling on a curved track.

It is also worth mentioning that a Type-5 DAC was missed for the verification of electric coupling. This test should be undertaken in the future, as the functionalities offered by electric coupling are fundamental in order to simplify the train data generation process or the automatic braking test, which will reduce exponentially the stay times of freight trains at logistic terminals.

In the last place, hybrid DAC for locomotives has been excluded from these tests but considering them for the next tests is deemed necessary, including some running safety/derailment tests supporting the future modification of the TSI's.